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Techno-economic feasibility of Energy Hubs located in rural communities in Malawi

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2019

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Signed: Marianne Monge Date: 22nd August 2019

Abstract

The sustainability of off-grid systems has remained an ongoing challenge for practitioners due to technical and economical limitations in many developing countries. Recent studies on productive use of energy conducted in Malawi documented that an Energy Hub scheme delivered under an ownership social enterprise model is expected to be a more sustainable energy delivery model in rural communities. To evaluate if such Energy Hub scheme can be applied successfully, there is a need to analyse different Energy Hub configurations identifying the optimum configuration that brings in enough revenue, year on year, to keep the system operational.

The aim of this study is to evaluate the viability of the deployment of Energy Hubs in rural communities in Malawi identifying the optimal Energy Hub configuration and battery's DoD as well as how many Energy Hubs installations need to be deployed to keep cash flow positive. The approach taken involves the development of an Energy Hub tool that allows the assessment of the viability of different Energy Hub configurations based on the ability of the system to keep a positive cash flow while minimising the upfront grant and maximising the capital recovery.

The outcome of this study shows that distinct Energy Hub configurations have different ability to accumulate cash (capital recovery) over the lifetime of the project, but none of the configurations could recover 100% of the initial CAPEX. Considering that the Energy Hub will be delivered under the CEM model (a social enterprise) the percentage of CAPEX recovered would be reinvested into other energy access initiatives. Therefore, although the Energy Hub model is not financeable from standard loans, upfront grants can enable not just the Energy Hubs schemes, but wider impact in rural communities. The results also show that the optimal Energy Hub configuration considering the battery's DoD is the configuration modelled in the baseline + irrigation scenario with a battery DoD of 50% as it presented the best balance of keeping the cumulated cash flow positive, minimising upfront grant required to deploy a minimum of five installations and it is capable of recovering 54% of the initial CAPEX.

Results of the survey developed in partnership with CEM should be analysed to generate input data for the Energy Hub tool and enable wider application in future projects. Further research needs to be focused on Energy Hubs configurations considering DC appliances as it can minimise overall costs of the system.

Acknowledgements

Throughout the writing of this dissertation I have received crucial support and assistance. I would first like to thank my project supervisor, Mr Damien Frame, for providing advice and guidance. I would like to acknowledge my colleagues from the Energy for Development research team and Community Energy Malawi for their collaboration and support during the development of my project. In addition, I would like to thank Iberdrola Group for the financial support throughout this year of study, and to my family for their wise counsel and encouragement. Finally, I would like to give special thanks all my lecturers and classmates on the MSc Renewable Energy Systems and the Environment course who have all contributed to making this year an enriching and enjoyable experience.

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List of Abbreviations

AC	Alternating current
CAPEX	Capital Expenditure
CEM	Community Energy Malawi
DC	Direct current
DoD	Depth of Discharge
EBIT	Earnings Before Interest and Taxes
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization
EBT	Earnings Before Taxes
ESMAP	Energy Sector Management Assistance Program
E4D	Energy for Development
FAO	Food and Agriculture Organization of the United Nations
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
MERA	Malawi Energy Regulatory Authority
MBS	Malawi Bureau of Standards
MPPT	Maximum Power Point Tracker
NPV	Net Present Value
OPEX	Operational Expenditure
PUE	Productive Use of Energy
PV	Photovoltaic
SOGERV	Sustainable Off-Grid Electrification of Rural Villages
SPIS	Solar Powered Irrigation System
SSA	Sub-Saharan Africa
SSE	Surface Meteorology and Solar Energy
UoS	University of Strathclyde

1. Introduction

1.1 Background

Electricity access is a crucial enabler of development, widely recognised as a fundamental infrastructure for all sectors and highlighted in the United Nation's Sustainable Development Goal 7 as a global priority with very high development impact [1, 2]. It is acknowledged that electrification facilitates enterprise development and enables new potentials for income generation. Conversely, limited electricity access is a significant barrier to economic and social development in some continents of the world.

Malawi, in Sub-Saharan Africa (SSA), ranks near the bottom of the Human Development Index [3] and the need for electricity access is severe. Only 9% of the population has access to electricity with 16.8 million people living without power [4]. Over 50% of the population lives below the poverty line, the majority of which live in rural areas with no prospect of connecting to the national grid.

To date, off-grid renewable-based systems have presented the most viable option to achieve electricity access [5]. As a result, over the last 10 years, stand-alone solar photovoltaic (PV) systems have been deployed in rural Malawi improving electricity access [6].

In the context of Malawi, off-grid solutions generate electricity for domestic or productive use, typically supplying a single household (pico-solar products) or a local community (solar microgrids) [6]. An off-grid stand-alone PV system is commonly comprised of a PV module, charge controller, energy storage, inverter and several loads.

The pico-solar products deployed in rural Malawi generally succeed in providing to communities a Tier 1 level, while solar microgrids are able to provide Tier 2–3 levels of electricity access enabling the development of local businesses with higher power appliances [7,8]. The tiers are based on Energy Sector Management Assistance Program (ESMAP), which is a standardised multi-tier framework that measures the quality of electricity access and defines ascending tiers of electricity access (0–5) [9]. Figure 1 illustrates the categories of each tier and the respective quality of power supply.

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	No electricity	1-50W	50-500W	500-2000W	>2000W	
Duration	<4hrs	4-8hrs		8-16hrs	16-22hrs	>22hrs
Reliability	Unscheduled outages				No unscheduled outages	
Quality	Low quality			Good quality		
Affordability	Not affordable		Affordable			
Legality	Not legal			Legal		
Health & Safety	Not convenient				Convenient	

Figure 1: Quality of Power Supply for each energy access tiers. [4]

According to ESMAP, Tier 0 defines customers with no electricity access, while higher level tiers define customers with levels of electricity access commonly associated with a reliable grid connection.

1.2 Motivation

The deployment of pico-solar products and solar microgrids in rural communities in Malawi has a significant effect on the health and quality of life of those living off-grid, as well as the development of commercial activity through productive uses of energy (e.g., barber shop, phone charging, etc.) [10]. However, the sustainability of off-grid systems in Malawi (as well as a wider developing country context) has remained an ongoing challenge for practitioners due to technical and economical limitations that restrict the move from lower to higher tiers generating a clear energy access gap between Tier 1 and Tier 5 [6].

The lack of a successful sustainable system delivery model to fulfil the gap at Tier 4-5 combined with the commitment of the Government of Malawi and international donor funding bodies in supporting the development of rural electrification is the main motivation to conduct a study in this particular area.

Recent studies related to productive use of energy (PUE) conducted in Malawi by Energy for Development (E4D) team in partnership with community energy Malawi (CEM) documented that the deployment of Energy Hubs, which is an off-grid stand-alone PV system providing electricity to co-located businesses, is expected to be a more organic and sustainable model of delivering off-grid PV systems than deploying PV stand-alone systems for distributed business as the energy provision becomes a shared concern of the entrepreneurs housed within the Energy Hub. Although some studies identify the potential of Energy Hubs that will be delivered through a social enterprise ownership, which in this case is CEM, no feasibility study to evaluate the viability of Energy Hub has been yet completed.

The access to long-term finance for capital and the ability to absorb short-term negative cash flow are challenges for CEM. Therefore, a financial model that requires a donor grant is necessary to allow the deployment of Energy Hubs. To evaluate if such Energy Hub schemes can be applied successfully within rural communities in Malawi, there is a need to analyse different Energy Hubs configurations identifying the optimum configuration that brings in enough revenue, year on year, to keep the system operational and to run the central organisation.

1.3 Project Aim and Scope

The aim of this study is to evaluate the viability of the deployment of Energy Hubs in rural communities in Malawi identifying the optimal Energy Hub configuration and battery's DoD as well as how many Energy Hubs installations need to be deployed to keep cash flow positive, as well as evaluating what are the implications for upfront grants. This aim was met by the completion of the following tasks:

1. Overview of relevant literature and previous practical work to understand the challenges while deploying off-grid system in rural communities and collect representative data to build Energy Hub tool;
2. Development of Energy Hub tool including determination of likely daily energy consumption and peak power requirements of each PUE, establishment of different scenarios, development of load profiles, identification of appropriate system design, evaluation of lifetime of system components, definition of total capital expenditure (CAPEX) and operational expenditure (OPEX) of the system, assessment of suitable cost recovery mechanisms through a funding structure, preparation of financial statements over a 20-year horizon.
3. Engagement and practical consultation with CEM including development of structured questionnaires and survey conduction.

4. Evaluation of the robustness of the results generated by the Energy Hub tool through a sensitivity analysis of relevant parameters.

The main outcome of the study is the Energy Hub excel tool that allows the assessment of the viability of different Energy Hub configurations and identifies the optimal configuration considering the ability of it to keep a positive cash flow while minimising the upfront grant and maximising the cash in the bank over the system life time (capital recovery).

The work does not consider any detailed studies on willingness to pay for a specific location in Malawi due to time constraints, although the results generated for the monthly payments are compared with previous studies on willingness to pay conducted in Malawi. Out of scope is also the specific infrastructure design of the irrigation system, although the estimated costs of building it is considered in the study.

2. Methodology

This study begins with a literature review on rural electrification of communities in SSA using off-grid solar PV, including a background of different off-grid solar PV system categories (pico-solar products and microgrids) and an overview of the main technical, economic and social challenges and barriers that reduce the overall off-grid PV system's sustainability and constrain the deployment of these systems with a Tier 4-5 level of electricity access focusing on PUE (chapter 3).

The literature review is then followed by the steps considered to generate all relevant information that are linked to the development of the Energy Hub tool (chapter 4, 5, 6, 7, 8, 9, 10 and 11). A brief description of the research methods used and how data was gathered in each chapter mentioned above is as follows:

Step 1. Development of likely daily energy consumption and peak power requirements of each PUE considered in the analysis. The selection of appropriate PUE types and usage patterns are based on surveys undertaken by previous studies (chapter 4).

Step 2. Establish four scenarios selecting different combinations of PUE types and develop the respective load profiles to further determine the best Energy Hub configuration (chapter 5).

Step 3. Determination of appropriate design and component sizing for the off-grid PV system for each scenario described in step 2 (chapter 6).

Step 4. Evaluation of component lifetime including PV modules, charge controller, battery bank, inverter and auxiliary components. The determination of the lifetime for all components, except battery lifetime, was based in a study carried out by the National Renewable Energy Laboratory (NREL). The battery lifetime has been determined according to an equation that combines two parameters to estimate the battery's total lifetime. This equation was developed by the author (chapter 7).

Step 5. Definition of the total CAPEX of the system for each scenario described in step 2 considering the different depths of discharge (DoD) mentioned in step 3.b. The CAPEX can be described as the sum of generation cost, storage cost, conversion cost, distribution cost, protection cost, metering cost, installation cost, infrastructure cost, equipment cost and project development cost (chapter 8).

Step 6. Forecasting the total annual OPEX of the system for each scenario described in step 2 over a 20-year horizon. The OPEX can be described as the sum of metering fees cost, generation and distribution maintenance cost (defined as a percentage of the total CAPEX) and fixed costs (include land rental and labour). The OPEX calculation for subsequent years considers the inflation rate (chapter 9).

Step 7. Definition of appropriate funding structure including cost recovery mechanisms to determine the deposit fee, arrangement fee and monthly payments for each scenario described in step 2 (chapter 10).

Step 8. Development of financial statements (income statement and cash flow) for each scenario described in step 2 to determine the necessary number of systems to be deployed to sustain the on-going operational costs of the deployed systems and the central operations of a social enterprise as well as to identify the final percentage of the CAPEX recovered over a period of 20 years (chapter 11).

The Energy Hub tool development was then followed by a survey creation in partnership with CEM. Structured questionnaires were developed to gather quantitative and qualitative data related to the PUE types that have been considered in the Energy Hub tool to generate more representative input data for the Energy Hub tool and then, generate appropriate results for specific locations (chapter 12).

A sensitive analysis of five relevant parameters (deposit rate, number of monthly payments, nominal discount rate, inflation rate and collection success rate) is performed (chapter 13) to test the robustness of the results generated by the Energy Hub tool in the presence of uncertainty. The results are then, presented with the selection of the most appropriate system to be deployed considering each scenario and within the scenarios (chapter 14).

The main results are discussed against the stated aim along with some wider implications highlighting the further study that needs to be done for a successful project implementation (chapter 15) and finally, the project is concluded (chapter 16).

Figure 2 shows the flow chart with a summary of the research methodology adopted by the author to develop this study.

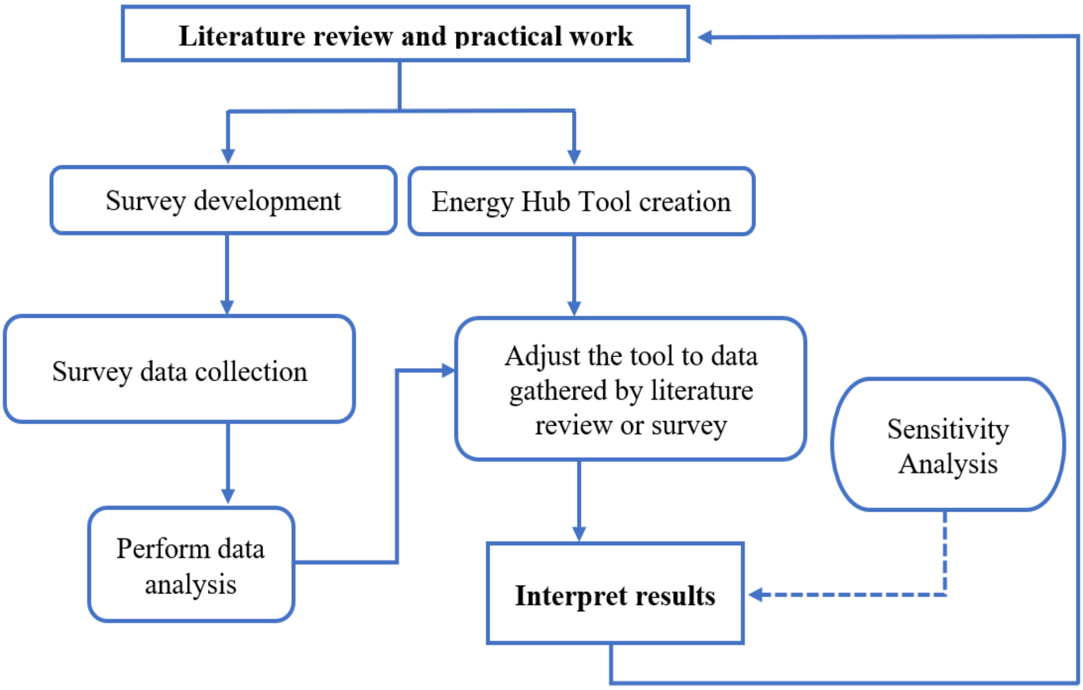

Figure 2: Flow chart with a summary of the research methodology.

3. Literature Review

The literature review section reviews the principles of PUE, explores the promotion of productive use through standalone solar systems and solar microgrids aerobic digestion, gives an overview of case studies on PUE, presents the challenges to uptake and finally, a discussion on how an Energy Hub can address these challenges.

3.1 Productive use of energy

In a simplified term, productive uses of energy are the activities that increase income or productivity [11, 12, 13]. The working definition that will be used for the purpose of this study is following the approach developed in Productive Use of Energy (PRODUSE) Manual. A productive use of energy is defined as "agricultural, commercial and industrial activity involving electricity services as a direct input to the production of goods or provision of services" [11].

In an unpublished World Bank paper, K. Kapadia defines that the rationale behind the promotion of PUE is based in three distinct goals described as follows [14]:

1. PUE maximizes the economic and social benefits of energy access. The development of energy projects including productive use components have more changes to provide rural economic development than energy projects that merely focus on the electricity provision.
2. The incorporation of productive uses into energy projects facilitates the achievement of the Millennium Development Goals.
3. Rural electrification programmes including productive use component have more chances to achieve economic and financial sustainability due to the higher ability to pay of enterprises that generate profits through electricity use and facilitation of funding procurement as rural financing bodies see more value on productive investments.

Considering the rural context in many developing countries, most typical productive uses can be identified in agricultural activities (e.g. irrigation and grain milling), different manufacturing activities such as welding, ice making and carpentry, as well as the activities offering a service, e.g. barber shops, mobile phone charging and other facilities that use electricity for television, sound systems and refrigeration.

There are significant opportunities in many SSA countries to invest in PUE projects. According to International Food Policy Research Institute, only 4% of arable land is under irrigation, even though the production of irrigated crop fields double or more compared to the production of purely rain-fed crop fields, and the significant higher income when selling crops grown during off-season due to the use of irrigation schemes [15]. An increase of approximately 20% to 70% in revenues and 50% to 200% in productivity is achieved by carpentry and tailoring businesses only by switching to electric appliances and equipment [16]. The population of communities lacking hair clippers, grain mills and mobile phone charging shops needs to travel long distances to the closest town that have access to these machines.

The promotion of productive uses through renewable energy sources is even more suitable in the rural context as it offers environmental benefits over fossil fuel sources and there is international funding available for development of projects focusing on renewable energy. The access to clean and reliable electricity for local businesses in rural communities combine both social and environmental benefits in a sustainable way. Table 1 presents examples of different energy services and their income generating value.

Table 1: Examples of different energy services and their income generating value. [17]

Energy Services	Income Generating Value	Renewable Energy Services
Irrigation	Better yields, higher value crops, greater reliability, growing during periods when the market prices are higher	Wind, PV solar, biomass, micro-hydro
Illumination	Reading, extending operating hours	Wind, PV solar, biomass, micro-hydro, geothermal
Grinding, milling, husking	Create value-added product from raw agricultural commodity	Wind, PV solar, biomass, micro-hydro
Drying, Smoking (Preserving with process heat)	Create value-added product, preserve product to enable selling in higher-value markets	Biomass, solar heat geothermal
Expelling	Produce refined oil from seeds	Biomass, solar heat
Transport	Reaching markets	Biomass (biodiesel)
TV, radio, computer, internet , telephone	Entertainment businesses, education, access to market news, coordination with suppliers and distributors.	Wind, PV solar, biomass, micro-hydro, geothermal
Battery charging	Wide range of services for end-users (phone charging business)	Wind, PV solar, biomass, micro-hydro, geothermal
Refrigeration	Selling cooled products, increasing the durability of the products	Wind, PV solar, biomass, micro-hydro

3.2 PUE through standalone solar systems and solar microgrids

Many of PUE projects deployed in SSA are provided through off-grid PV systems due to the abundance and availability of solar resources in this region. The use of standalone solar system is the most popular application of PV technology for productive use in many SSA countries. In recent years, there is an increase in the inclusion of PUE businesses in microgrids deployed. An overview of case studies of off-grid PV projects (standalone solar systems and solar microgrids) deployed in SSA focusing on PUE businesses is presented in the next section.

3.2.1 Case studies of PUE

There are examples of projects deploying off-grid PV systems in SSA that target productive use. The projects's name, brief description and main outputs of each program are presented.

Case study 1 - Energy Douce

This project is developed in Republic of Congo in a partnership model between Energie Douce, which is a provider of solar powered systems and EnR Congo, which is a non-profit organisation that promotes sustainable development in African countries using renewable energy).

The project aims to support agricultural activities through the implementation of solar-powered mills that will facilitate the processing of cassava and some grain. In the scope is also included the installation of a solar-powered water pump system for an irrigation scheme. The maintenance of the installation will be carried by local users, so technical training will be provided as well [17]. This project was designed to be developed primarily in rural communities in Congo and subsequently expanded to rural communities in Gabon and Cameroon.

Case study 2 - Ensol Tanzania

This project is developed by Ensol Tanzania Ltd, which is a provider of solar powered systems offering supply, installation and maintenance of PV products and systems in south Tanzania.

The project aims to support the implementation of solar water pumping system for irrigation capable of supplying approximately 50 m^3 of water per day in eleven villages in Tanzania. For a long-term sustainability of the system, it was created a water committee in each village, which has the responsibility to collect a small contribution of the members of the scheme [17]. Scheme's members of eight villages are still having supply from the installed solar water pumping system.

Case study 3 - Mobisol GmbH

This project is developed by Mobisol GmbH, which is a Berlin-based social business delivering high-quality PV systems for houses and local business focusing on low-income customers in Tanzania and Rwanda.

The initiative aims to provide high quality PV systems with capacity to run small businesses in rural areas without prior reliable energy access and empower rural entrepreneurs throughout a range of different business kits. The energy delivery model is based in an affordable micro-financed fee plan consisted in monthly payments via mobile banking. [17] Mobisol is growing in East Africa and many entrepreneurs in rural communities select their energy delivery model to power small businesses to generate income.

Case study 4 - Phaesun GmbH

This project is developed in Somalia in a partnership model between Phaesun GmbH, which is a German company specialised in off-grid PV systems and Horn Renewables, which is a company based in Somalia aiming to promote off-grid energy in rural communities in Somalia.

The project partners have been developing and implementing off-grid PV solutions focusing on business needs. Some examples are the development of solar charging stations, solar cooling and refrigeration kits for shops, kiosk owners and fish-related activities [17]. Since the first introduction of the off-grid PV solutions in 2012, more than 30 solar charging stations for mobile phones and lamps have been implemented and 30 solar refrigeration kits have been installed at shops, kiosks, restaurants and fishermen places.

Case study 5 – Jumeme

This project is developed by Jumeme Rural Power Supply Ltd, which is a solar-powered minigrid operator supplying high quality and affordable electricity to rural communities in Tanzania. The pilot program targeted twelve local businesses providing support and financing for entrepreneurs to pay for the installed PV system and afford appliances.

This project is a successful example of how off-grid systems focusing on productive use can improve capacity utilization, provide additional revenue stream and create jobs in the local community [18].

3.3 Challenges

Despite successful projects outlined above, off-grid systems focusing on productive use remains outside the scope of most electrification efforts in SSA. There are many challenges involving the deployment of these systems in SSA such as estimation of demand, availability and cost of equipment, ability to pay of the customers and maintenance of the system [19]. In this study, additionally to the challenges mentioned above, other challenges were identified and discussed in the Energy Hub pre-feasibility study developed by researches of University of Strathclyde (UoS) E4D team. This study lists the most common technical and social challenges identified through field visits to installed PV systems deployed by the Sustainable Off-Grid Electrification of Rural Villages (SOGERV) project.

3.3.1 Technical challenges

There are many technical challenges while deploying off-grid PV systems, but most of them are related to inadequate use of the system by the local community. In many of the systems deployed by SOGERV, it is clear that the system's use is exceeding the installed system's capacity. The PV system is designed to support a number of official users and appliances, but unfortunately is common to find the following scenarios [6]:

- a set number of unofficially connected users to the PV system;
- unofficial external batteries being charged using the system battery bank in an ad-hoc manner and without any technical support;

- connection and use of appliances (such as speakers and fridges) that the system was not initially designed to support

Figure 3 shows an example of an unofficial connection in a rural community in Malawi. It is unknown whether the unofficial energy users are paying for their electricity use, or essentially having the electricity provision through the system for free.

Figure 3: Example of an unofficial connection in a rural community. [6]

Inadequate use of the system is a root cause of most of system failures. In addition is an issue that is difficult to address as it is related to behaviour actions. Some of the system failures are identified as follows [6].

- Battery misuse and lack of monitoring: battery over-use and no constant monitoring of battery health lead to eventual failure of the battery reducing the lifetime of the battery.
- Bypassing of charge controller: the charge controller is a device that prevent the damage of the batteries controlling the charging and discharging battery's cycles. When the charge controller is bypassed and heavy loads are connected, the battery bank is massively damaged in every deep discharge cycle. As a result, the lifetime of the battery bank reduces considerably.
- Improper battery ventilation: the ventilation for the battery bank is an important factor as it avoids the reduction of the lifetime of the battery due to effects of high temperatures. Although it is relevant, the battery ventilation is usually inadequate.

- Faulty and ad-hoc electrical wiring; not only a fire and electrocution hazard but also a cause of high electrical losses for the system. A field example of wiring is shown in Figure 4.

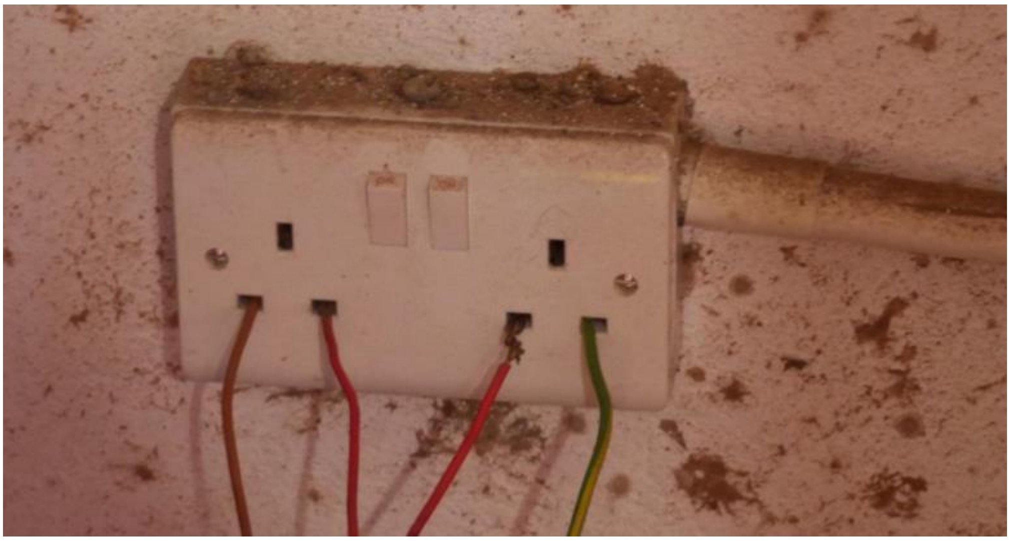

Figure 4: Field example of inadequate wiring in a PV system. [6]

3.3.2 Social challenges

In addition to the technical challenges, it was also identified social challenges.

- Low payment for electricity by users: many rural communities have a belief that the electricity generated through renewable sources is 'free' leading to low payments that cannot sustain the maintenance and replacement of components over the project's lifetime.

- Belief that PV systems do not work: the misuse of the system combined with the limited local ability to manage and maintain PV installations leads to a damaged reputation of PV systems due to poor local understanding of simple maintenance tasks required.

3.4 Energy Hub as a solution

The term 'Energy Hub' can be used to describe different energy delivery models. The working definition that will be used for the purpose of this study is the one defined in Energy Hub pre-feasibility study. An Energy Hub is defined as "off-grid rural renewable energy system, delivering electricity to co-located (rather than distributed) businesses and community users. It will be delivered through a social enterprise ownership model, which, in this case, will be CEM, who have the technical expertise to correctly manage loads and protect the system but will also allow the community to use the system for high social impact uses" [6].

The Energy Hub can be physically defined as follows [6].

- An off-grid PV system installation + storage sized to a pre-selected number of small business and community activities. The ideal is to combine different businesses and activities within the system, so the load profile variability is smoothed.
- Building infrastructure allows better protection of the system with hidden wiring within the walls and battery bank with no ease access to support the selected businesses and community activities.
- Technical monitoring and fair fee payments: the businesses will be regulated, electricity use will be monitored and the users will pay affordable fee that will sustain the maintenance of the system and model.
- Community use of electricity and spaces by the businesses selected to integrate the system. The room infrastructure and necessary equipment is also provided.

The Energy Hub can be structurally defined as follows [6].

- The Energy Hub energy delivery model uses the economics of scale to reduce the capital expenditure of off-grid PV installations in rural communities in Malawi.
- A social enterprise will provide support and mentoring in a consistent way to the users of the systems and community members.
- On-site business support for the selected businesses within the system in order to educate users on the importance of electricity and potential profits when using it correctly.
- Funding structure with soft finance options for start-ups allowing local vulnerable people to start a business within the Energy Hub.

Through the Energy Hub energy delivery model, PV system failure and low impact will be mitigated. Table 2 summarises the risks while deploying off-grid PV systems and provides an explanation on how the Energy Hub energy delivery model will mitigate against the identified risks.

T*able 2: The root causes of system failure, the literature review findings and lessons learnt and the expected effect of the Energy Hub. [6]*

Root causes of system failure	***Literature review findings and SOGREV lessons learnt***	***How will the EnergyHub address the risk?***
Improper battery use and monitoring; Battery over-use and misuse (fully draining the battery) leading to eventual failure of the battery before the end of the battery life.	Improper battery use and monitoring is observed in literature and is still considered a high risk for the SOGREV project	The batteries will be housed in a controlled environment and therefore more easily protected from misuse. Through proper on-site supervision, energy use can be monitored to protect the battery usage
Faulty and ad-hoc electrical wiring; not only a fire hazard but also a cause of high electrical losses for the system.	Faulty and ad-hoc electrical wiring is common in Malawi and was observed at SOGREV project sites	By integrating the wiring into the walls the official system wiring will be protected and all businesses will be provided with adequate wiring for their business purpose
Low user payments for electricity; The local belief that renewable electricity is 'free' (rather than the energy) leads to low payments that cannot cover the maintenance and repair once a failure occurs.	A common source of low sustainability of energy systems is the lack of a properly managed maintenance and repair fund	As the local community will be paying an 'all-inclusive' rental fee for their business space, the maintenance and repair will be built into the fee, allowing for any repairs to be carried out
Limited local ability to manage an electrical PV installation; the lack of singular local management of the system allows people to charge and adapt the system at will, leading to overloading.	In Malawi there is limited local ability to manage an electrical PV installation properly and overloading through 'unofficial' connections is common	The economics of scale allows for on-site management to mitigate against overloading through 'unofficial' connections
Failure of a PV system will damage local trust in renewable energy as a viable source of electricity and may convince local communities that solar PV installations 'don't work'	Lack of energy standards in Malawi is identified by rural communities and central organisations (such as MERA and MBS) as a high risk to solar energy sustainability as public trust in solar energy is damaged by failures	The EnergyHub is key to proving solar energy as a viable renewable resource that can be trusted to deliver electricity. Correct management of the PV system and the expectations of the local community from the PV system will foster trust in solar PV from the business owners
PV installation managed by the local community without any regulation	Many PV systems are managed locally with limited training in technical, managerial and financial aspects of running a PV system. SOGERV addresses this risk through extensive local training for these three areas	An energy hub will allow for on-going research into the type and level of knowledge that is needed to correctly run a PV system in rural Malawian locations

4. Selected productive use of energy types

The first part of the Energy Hub tool is to select PUE types to be included in the scenarios. CEM conducted market assessments in 2015 to evaluate the interest and need of different PUE in different remote communities in Malawi. The result of these assessments showed that small sales and services business (including phone charging, groceries, barber shop and video show), irrigation farming and maize mill are the PUE that present higher chances to be viable according to the survey analysis [20]. As a result, this study includes only these PUE types in order to reduce the risk of deploying some PUE that are not priority for the rural communities.

The calculation of the daily energy consumption of each PUE selected is extremely important to determine the appropriate Energy Hub power generation system design and financial modelling. The daily energy consumption (E_d) is calculated as follows.

$$E_d = \sum_{a=1}^{x} hW_a \qquad (1)$$

where, h is the time of operation of the appliance and W is the wattage of appliance. Hence, the sum is calculated for the total amount of appliances x.

4.1 Small sales and service business

The examples of the sale and services shops in this study include phone charging, groceries with different energy consumptions, barber shop and video show. Table 3 presents the alternating current (AC) appliances and respective power ratings that have been considered.

Table 3: AC appliances and power ratings for small sales and service business.

Appliances	Power Rating (W)
Indoor Lights	5
Phone Charging	5
Hair clipper	15
Radio	5
Fridge	100
Fan	75
TV	75
Stereo	50
DVD Player/Decoder	20

For the calculation of daily energy consumption of each business some assumptions were made [20]:

- Phone charging: Lights are switched on for 3 hours, radio and phone charging for 13 hours;
- Grocery 1: Lights are switched on for 3 hours and radio for 12 hours;
- Grocery 2: Lights are switched on for 3 hours, radio for 12 hours and fan for 4 hours;
- Grocery 3: Lights are switched on for 3 hours, radio for 12 hours and fridge has a 12-hour cycle;
- Barber shop: Lights are switched on for 3 hours, radio for 12 hours, fan for 4 hours and hair clipper for 10 hours;
- Video show: Lights are switched on for 4 hours, TV for 5 hours, stereo for 5 hours and DVD Player/Decoder for 3 hours;
- The working hours for all business are the same during weekdays and weekends;

The daily energy consumption reduces in June due to the lower temperature and consequently, no use of fan. The appliances that each PUE type has and its respective daily energy consumption along the year are presented in Table 4.

Table 4: Daily energy consumption for different PUE types along the year.

										July - May	June
PUE Type	**Indoor Lights**	**Radio**	**Phone charger**	**Fan**	**Fridge**	**Hair clipper**	**TV**	**Stereo**	**DVD Decoder**	**Total Daily Energy per PUE (kWh)**	**Total Daily Energy per PUE (kWh)**
Phone Charging	*	*	*							0.37	0.37
Grocery 1	*	*								0.11	0.11
Grocery 2	*	*		*						0.41	0.11
Grocery 3	*	*			*					1.32	1.32
Barber Shop	*	*		*		*				0.56	0.26
Video Show	*						*	*	*	0.77	0.77

4.2 Irrigation farming

Irrigation is the artificial and controlled application of water for agricultural purposes through systems that fulfil the water needs of crops when it is not completely satisfied by rainfall. A solar irrigation scheme is illustrated in Figure 5.

Figure 5: Example of solar irrigation. [20]

In Malawi, crop irrigation is a crucial activity as the population highly depends of agricultural activities to generate income. Currently, the use of diesel generators to power water pumps is prevalent. However, the diesel price is one of the highest in the world at £0.81 per litre [21], with an expected increase by 6% annually. In addition, diesel generators contribute to harmful levels of air pollutants. Thus, solar powered pumps can be a good alternative for irrigation systems as it has a lower OPEX compared to diesel powered pumps.

To determine the water pump size, it is necessary to estimate the total daily water need and the estimated total dynamic head of the irrigation system. For this calculation, the solar powered irrigation system (SPIS) Toolbox was used. This Toolbox was developed by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in collaboration with the Food and Agriculture Organization of the United Nations (FAO), under the global initiative Powering Agriculture: An Energy Grand Challenge for Development [22].

For the calculation of the water need, some assumptions were made:

- Dedza area in Malawi has a clayey soil texture [23];

- Crops that have been considered are maize, rice, sorghum and wheat [24];
- The irrigation scheme has 10 members in total. Each member has an estimated 0.4 acre of land [6], where 0.1 acre is cultivating maize, 0.1 acre is cultivating rice, 0.1 acre is cultivating sorghum and 0.1 acre is cultivating wheat;
- The members can plant two times in a period of one year [22];
- All crops have an average growing time and the cropping density is set to normal spacing [22];
- The irrigation scheme is flooded through piped supply with an estimated total efficiency of 80% [22].

The crop sowing times, and its respective growing time are displayed in Table 5.

Table 5: Crop sowing time and average growing time.

Type	Maize	Rice	Sorghum	Wheat
Start of sowing time	15th October	15th November	1st December	1st November
	15th April	15th May	1st June	1st May
Average crop growing (days)	110	150	130	150

Mean daily temperature (°C), rainfall (mm/month) and all crop information was inputted to SPIS Toolbox. The daily water need calculation was calculated for 1 member and then scaled up to ten members. The water need of each crop, total daily water need per member as well as for the irrigation system is showed in Table 6.

Table 6: Crop sowing time and average growing time.

General Geographic Information

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Mean daily temperature (°C)	23	23	22	21	19	17	17	18	21	24	24	23	summer months
Rainfall (mm/month)	298	268	230	84	23	12	8	8	8	29	124	281	rainy season

Irrigation Schedule - Daily crop water need

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0.1 acre	Maize	0	0	0	0	1.5	2.2	0.0	0.0	0.0	0.8	0.8	0	(m^3/day)
0.1 acre	Rice	0	0	0	0	1.5	2.0	2.5	1.5	1.2	0.0	0.5	0	(m^3/day)
0.1 acre	Sorghum	0	0	0	0	0.0	0.9	1.7	2.3	1.7	1.2	0.0	0	(m^3/day)
0.1 acre	Wheat	0	0	0	0	1.1	1.9	2.3	1.4	1.1	0.0	0.2	0	(m^3/day)
0.4 acre	Total each member	1	1	1	1	4.1	6.9	6.5	5.2	4.0	2.0	1.5	1	(m^3/day)
4 acre	Total (m^3/day)	10	10	10	10	41.2	69	64.8	51.6	39.5	20.1	15.4	10	

As we can see on the table, the daily water need varies along the year, with low daily water needs during the rainfall season. The maximum daily water need occurs in June with a total water need of 69m³ per day. During the rainfall season, there was no need for the irrigation system. However, as the forecast changes along the years, it was added a minimum water need of 1m³ for each member of the scheme.

The SPIS Toolbox also calculates the estimated total dynamic head of the irrigation system. In this study, the irrigation system includes a water tank storage which replaces the need of a battery bank reducing the cost of the overall system.

For the calculation of the estimated total dynamic head of the irrigation system, some assumptions were made [20, 22]:

- The static water level is 15 meters;
- The drawdown is 2 meters;
- The elevation difference well to tank stand is 0.5 meters;
- The height of tank inlet from ground is 5 meters;
- The height of tank outlet is 2 meters;
- The head loss in water meter is 0.5 meters.
- Total pump pressure loss in valves and fitting is 0.25 meters;
- Total irrigation pressure loss in valves and fitting is 1.5 meters.

Considering these assumptions, the estimated total dynamic head of the irrigation system is 24 meters.

Combining the information gathered of the total daily water need and the estimated total dynamic head of the irrigation system, it is possible to select the size of the AC water pump needed which it should be around 1.5 kW considering that solar operated systems are dependent on a minimum of 6 sun hours/day, which is readily available in many parts of SSA even during winter months [25].

It was estimated that the water pump will work for five hours per day between May and November, and for three hours per day between December and May as the daily water need during the rainfall is highly reduced. The daily energy consumption of the irrigation business along the year are presented in Table 7.

Table 7: Daily energy consumption for the irrigation PUE type along the year.

		May - November	Dec - April
PUE Type	**Water pump**	**Total Daily Energy per PUE (kWh)**	**Total Daily Energy per PUE (kWh)**
Irrigation	*	7.50	4.50

4.3 Maize milling

Maize milling is an agro-processing activity which transforms the maize grain into maize flour. Maize is the main staple crop grown and eaten in Malawi. 96% of maize consumed in Malawi is produced in Malawi [26], and the average maize consumption in Malawi is estimated in 130kg/person per year [27]. Figure 6 illustrates a solar maize mill machine.

Figure 6: Example of a solar maize mill. [20]

During the harvest time, the maize is stored whole in woven basket silos and milled along the year. Maize grains are hulled and then, milled into flour. Maize milling is a year-round activity. However, it varies along the year, with higher demand during the harvest season.

For the calculation of energy consumption some assumptions were made:

- The working hours for the maize milling business are the same during weekdays and weekends;
- The harvest season is between March and September considering the sowing times and average crop days that have been considered in item 4.2;
- Lights are switched on for 3 hours.

As a study to evaluate the real demand for maize milling in the area where the system will be deployed was not conducted due to time constraints, a 1.5 kW maize mill was selected [28]. This capacity is considered small when compared to maize mills already in operation in the main cities of Malawi, but this choice was necessary to guarantee that this activity would have enough demand all year round when implemented in a village, which has lower demand than bigger cities.

It was estimated that the maize mill will work for seven hours per day between March and September, and for three hours per day between November and February as the demand highly reduces in the months that are not during the harvest season. The appliances that the milling PUE type has and its respective daily energy consumption along the year are presented in Table 8.

Table 8: Daily energy consumption for the milling PUE type along the year.

			March - September	**November - February**
PUE Type	**Indoor Lights**	**Maize Mill**	**Total Daily Energy per PUE (kWh)**	**Total Daily Energy per PUE (kWh)**
Milling	*	*	10.59	4.59

5. Load scenarios

To size the Energy Hub appropriately, it is crucial to have an accurate understanding of the peak load and usage patterns of loads that will compose the system. In this study, four scenarios have been proposed to evaluate the impact of adding productive loads that have different usage patterns and large loads on the final Energy Hub design which consequently affects the CAPEX and OPEX of the system. In this study, the proposed scenarios are: Baseline, Baseline + Irrigation, Baseline + Mill and Baseline + Irrigation + Mill. The loads, its respective power consumptions and daily usage patterns that have been considered in each scenario are described in chapter 4 and more detail are shown in Appendix 1. With the understanding of the peak load and usage patterns of loads that compose each Energy Hub configuration, it is possible to determine for each scenario the Energy Hub daily energy demand presented in Table 9 and develop the Energy Hub load profiles presented in section 5.1, 5.2, 5.3 and 5.4.

Table 9: Energy Hub highest daily energy demand for each scenario.

PUE Type	Daily Energy per PUE (kWh)	Peak Energy per PUE (W)	Total Daily Energy per Scenario (kWh)			
			Baseline	Baseline + Irrigation	Baseline + Mill	Baseline + Irrigation + Mill
Phone Charging	0.37	40	0.37	0.37	0.37	0.37
Grocery 1	0.11	20	0.11	0.11	0.11	0.11
Grocery 2	0.41	80	0.41	0.41	0.41	0.41
Grocery 3	1.32	105	1.32	1.32	1.32	1.32
Barber Shop	0.56	95	0.56	0.56	0.56	0.56
Video Show	0.77	165	0.77	0.77	0.77	0.77
Irrigation	7.50	1500	0.00	7.50	0.00	7.50
Mill	10.59	1530	0.00	0.00	10.59	10.59
EnergyHub Monitoring	0.20	17	0.20	0.20	0.20	0.20
System daily energy with battery storage (kWh)			**3.72**	**3.72**	**14.31**	**14.31**
System daily energy with water tank storage (kWh)			**0**	**7.5**	**0**	**7.5**
System max power with battery storage (kW)			**0.52**	**0.52**	**2.05**	**2.05**
System max power with water tank storage (kW)			**0**	**1.5**	**0**	**1.5**

The energy hub monitoring has been included in the calculations, but it is not a type of business, although it must be included as it is necessary to run the system and there is an energy consumption associated with it.

It is expected that the load will grow along the years. However, there is no current study that can identify consistent trends in load growth. Therefore, the system size determined in chapter 6 have been designed to accommodate the developed load profile of each scenario described in the next sections.

5.1 Baseline

The Baseline scenario is composed by PUE types that provide small sales and service businesses for the community such as phone charging, groceries with different energy consumptions, barber shop and video show. This scenario does not have large loads and it has a peak load concentrate at night time with few loads occurring during morning time. More details of the loads, its respective power consumptions and daily usage patterns that have been considered to develop the load profile for the baseline scenario are shown in Appendix 1.

The real line graph presented a humped shape due to the assumption that the fridge runs on a 12-hour cycle. To reduce this distortion, a trendline was added as, in reality, the changes in the load profile are more graduated, with the fridge turning on and off on a minute by minute basis based on how often it is opened and the external ambient temperature. The trendline of the variation of daily load profile along the year for the baseline scenario is illustrated in Figure 7.

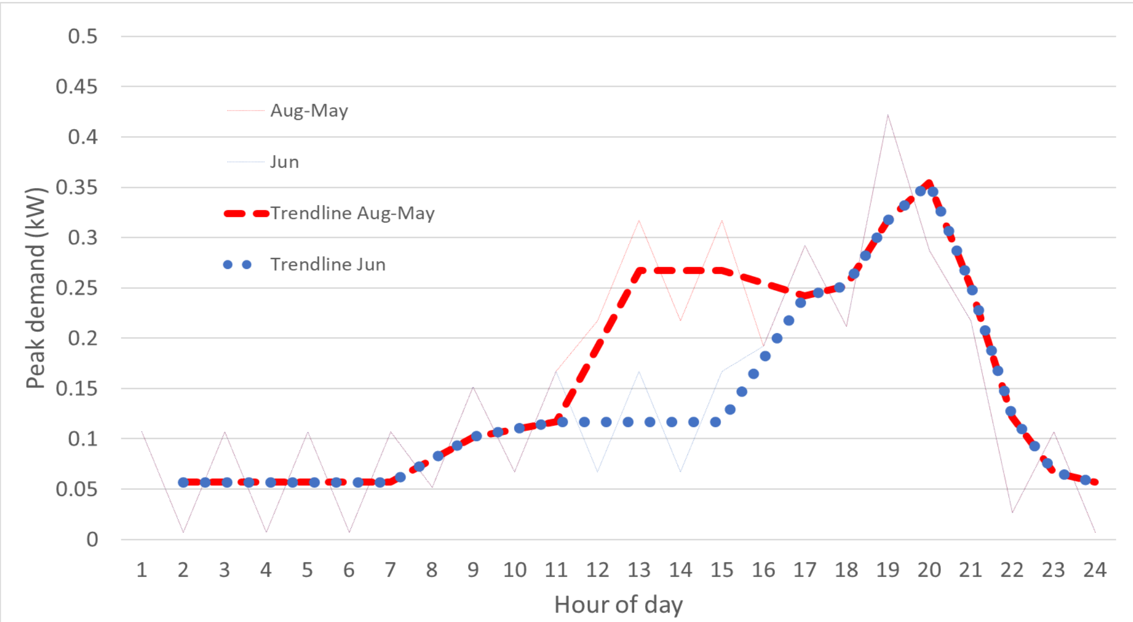

Figure 7: Variation of daily load profile along the year for baseline.

The developed load profile is compared to a referenced load profile for small business microgrids from existing literature [29] in Figure 8, which presents similar shape adding confidence to calculated load profiles.

As it is possible to see in Figure 8, the blue line illustrates a load profile of a microgrid that is composed by small businesses and it has a similar shape of the load profile that was developed for the baseline scenario, which is just composed by small businesses.

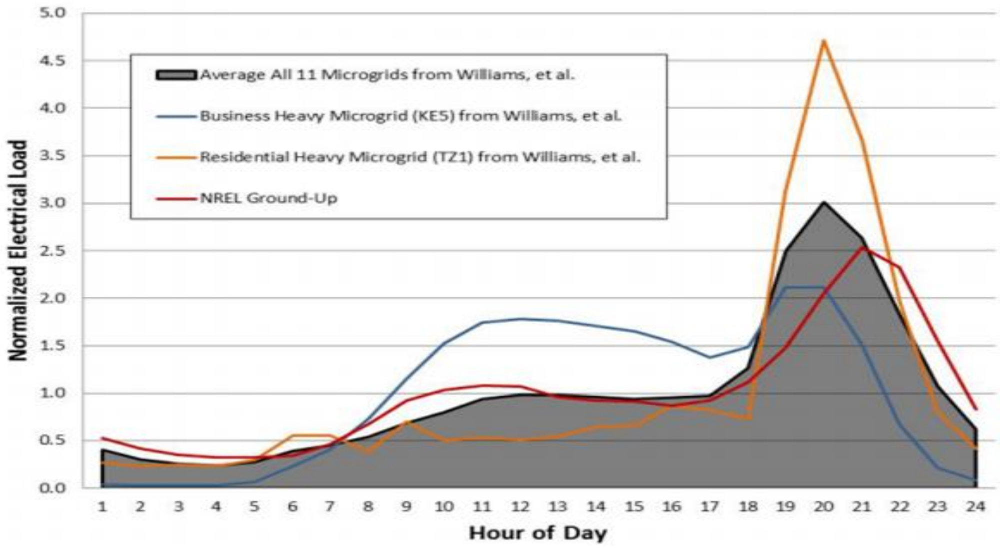

Figure 8: Normalized electrical load profile shape comparison. [29]

5.2 Baseline + Irrigation

The Baseline + Irrigation scenario is composed by PUE types described in topic 5.1 with the addition of irrigation farming. This scenario combines small sales/service businesses and basic agricultural use. This scenario has been included to evaluate the impact of end-use stimulation adding flexible loads (water pump) that can be useful to take advantage of excess solar. More details of the loads, its respective power consumptions and daily usage patterns that have been considered to develop the load profile for the baseline + irrigation scenario are shown in Appendix 1. The trendline of the variation of daily load profile along the year for the baseline + irrigation scenario is illustrated in Figure 9.

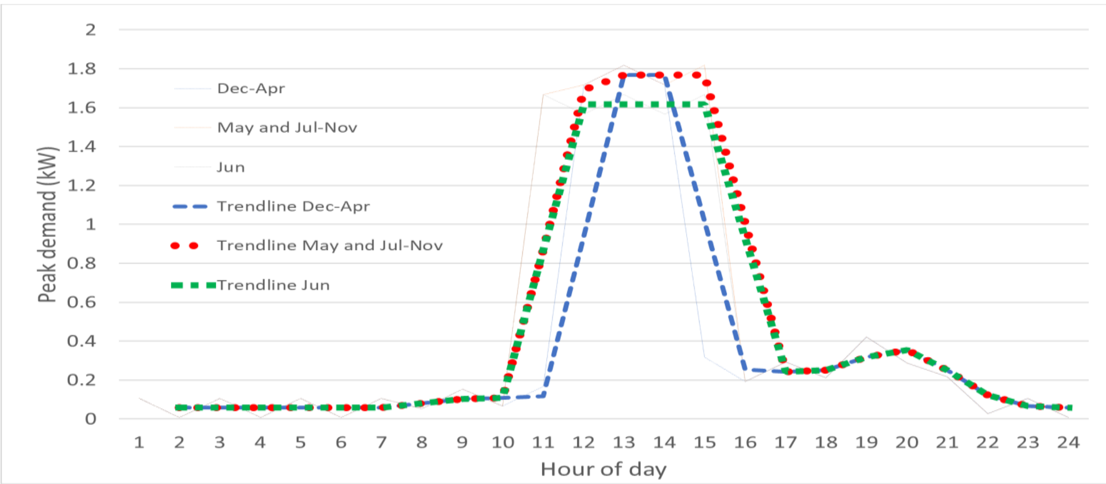

Figure 9: Variation of daily load profile along the year for baseline + irrigation.

The developed load profile is compared to a referenced load profile for end-use stimulation adding water pumping from existing literature [30] in Figure 10, which presents similar shape adding confidence to calculated load profiles.

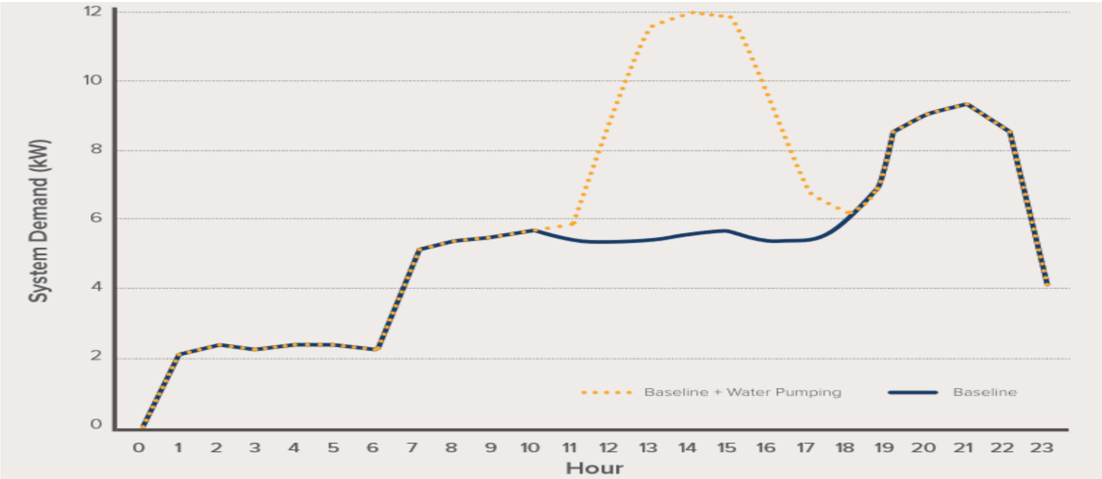

Figure 10: End-use stimulation with water pump. [30]

5.3 Baseline + Mill

The Baseline + Mill scenario is composed by PUE types described in topic 5.1 with the addition of maize milling. This scenario combines small sales/service businesses and value-added agricultural processing. This scenario has been included to evaluate the impact of end-use stimulation adding large daytime loads (maize mill) to increase the percentage of solar utilization. The trendline of the variation of daily load profile along the year for the baseline + mill scenario is illustrated in Figure 11.

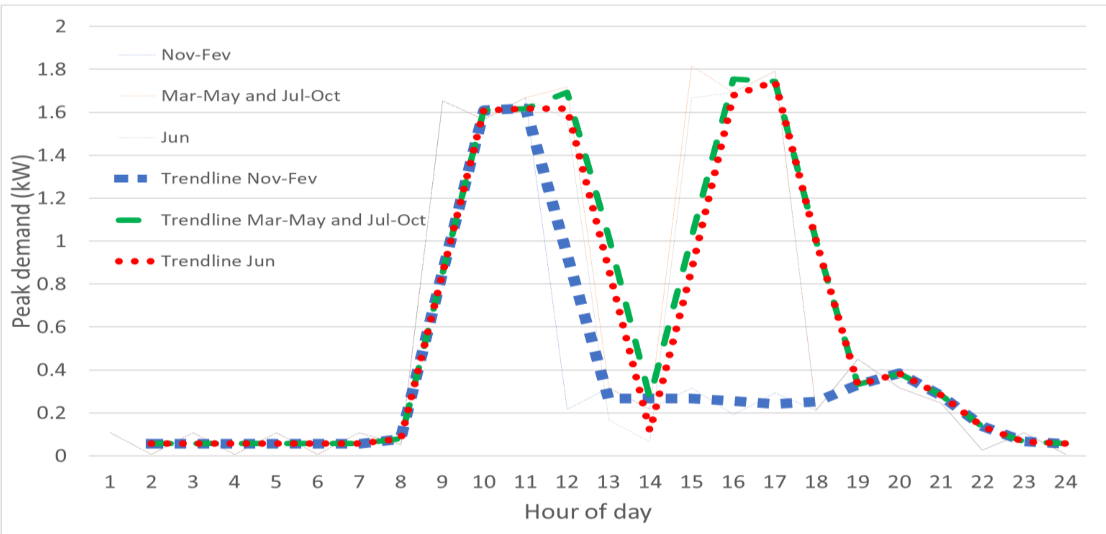

Figure 11: Variation of daily load profile along the year for baseline + mill.

The developed load profile is compared to a referenced load profiles for end-use stimulation adding grain mill from existing literature [30] in Figure 12, which presents similar shape adding confidence to calculated load profiles.

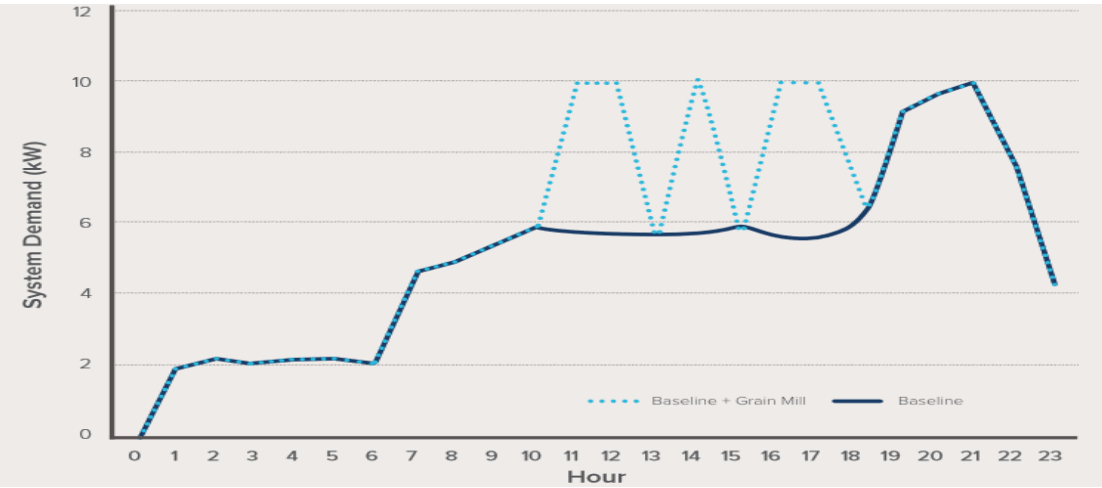

Figure 12: End-use stimulation with grain mill. [30]

5.4 Baseline + Irrigation + Mill

The Baseline + Irrigation + Mill scenario is composed by PUE types described in topic 5.1 with the addition of irrigation farming and maize milling. This scenario combines small sales/service businesses, basic agricultural use and value-added agricultural processing. This scenario has been included to evaluate the impact of end-use stimulation adding flexible loads combined with large daytime loads. The trendline of the variation of daily load profile along the year for the baseline + irrigation + mill scenario is illustrated in Figure 13.

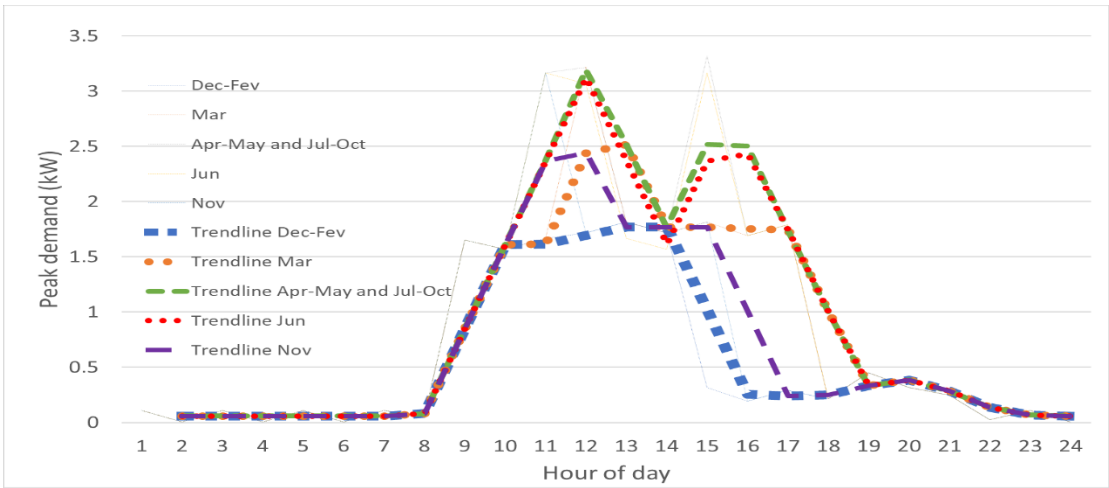

Figure 13: Variation of daily load profile along the year for baseline + irrigation + mill.

6 System Design

The basic components of the system are PV modules, charge controller, battery bank, inverter and cables. Scenarios that include baseline and mill require battery storage to guarantee the reliability of the off-grid system. In the other hand, irrigation system does not require battery storage. The reliability is fulfilled through a water tank storage system. Therefore, two systems have been proposed in this study. A schematic of the different systems is shown in Figure 14 and Figure 15.

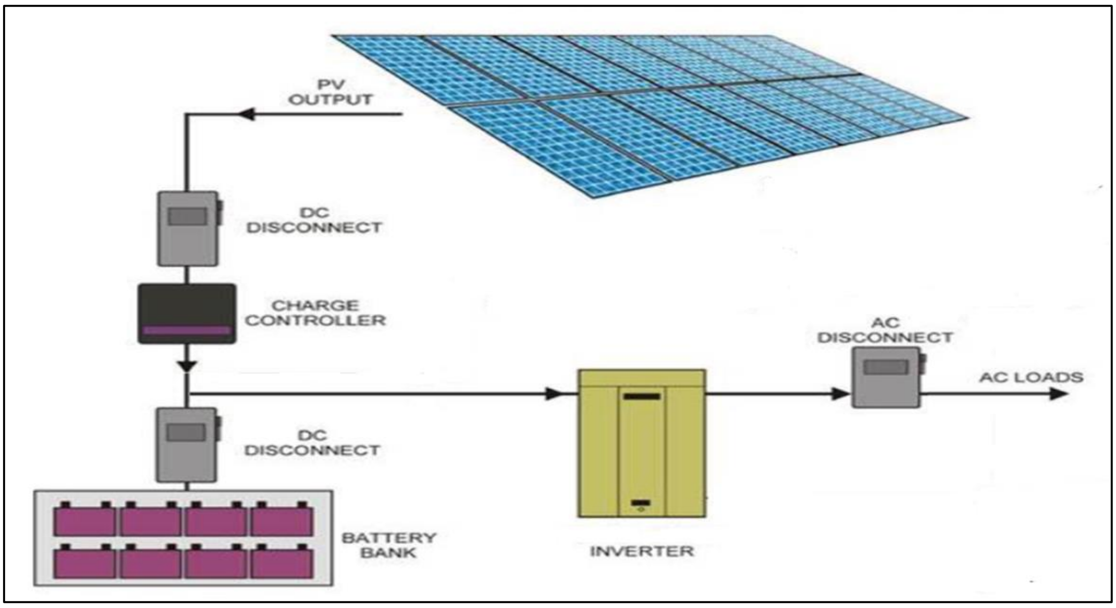

Figure 14: System schematic for small business and milling.

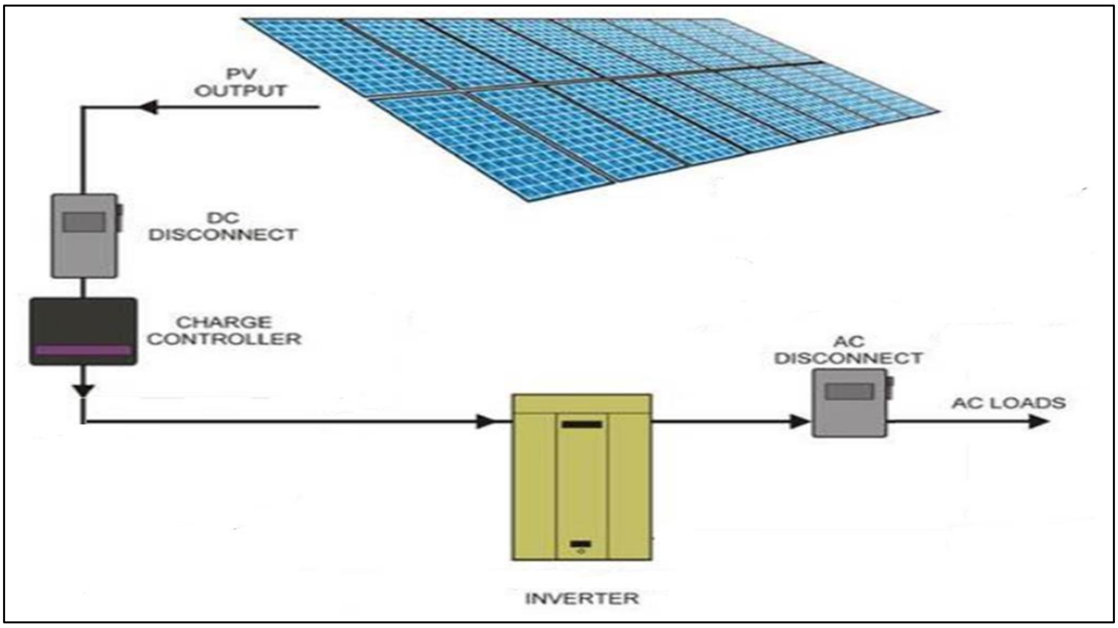

Figure 15: System schematic for irrigation.

6.1 Solar resource

Average monthly solar irradiation values used for the system design are from NASA Surface Meteorology and Solar Energy (SSE). The latitude and longitude measurements for Malawi location were input as -14.258714 and 34.340303, the resulting seasonal average daily radiation is shown in Figure 16.

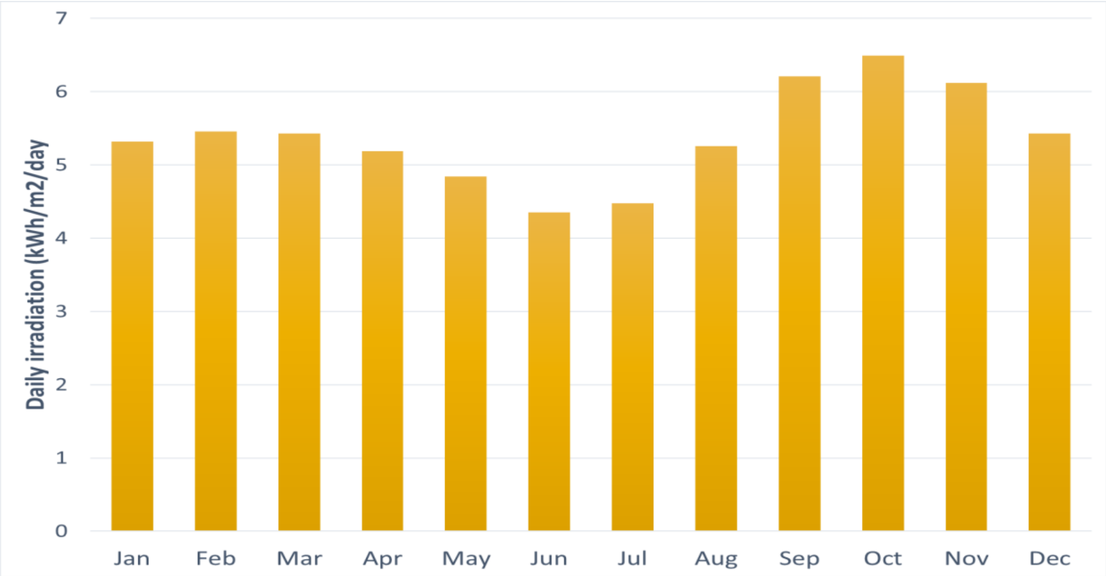

Figure 16: Average daily solar radiation in Malawi along the year.

To keep the reliability of the system in the worst possible case scenario, the lowest value was selected, which in this case occurs in June. Therefore, a scaled annual daily solar radiation of 4.35 kWh/m^2/day was used for the system design.

6.2 Component sizing

The size of components is based in standard design methodologies from the Malawi Bureau of Standards and Research and Development Division to determine the PV modules, battery's capacity and size other system components. The standards used are MS IEC /PAS 62111: 1999 [31], MS 695:2004 [32] and MS 696: 2004 [33].

Key design decisions and assumptions are shown in the Table X:

- System voltage is 48V;
- The system has an autonomy of 1.5 days;
- The efficiency of the system is 0.78;

- The safety factor is 1.25;
- Days of autonomy of the system is 1.5 days.

6.2.1 PV module

The PV module is the component of the system that converts sunlight directly into direct current (DC) electricity. To determine the size of the PV array, the technical specifications of the PV module that has been considered is shown in Table 10.

Table 10: Technical specifications of selected PV module.

Technical specification - PV Module	
PV module capacity (kW)	0.25
Voltage (V)	30.34
Current (A)	8.24
I_{SC} (A)	8.76
V_{OC} (V)	37.47
Array-to-load ratio	1.3

The PV system capacity required (C_{PV_s}) is calculated as follows.

$$C_{PV_s} = \frac{E_d R_{atl}}{S_d E_s} \tag{2}$$

where, E_d is the system daily energy required, R_{atl} is the array-to-load ratio, S_d is the daily solar radiation and E_s is the system efficiency.

The total number of modules required (N_{PV}) is calculated as follows.

$$N_{PV} = \frac{C_{PV_s}}{C_m} \tag{3}$$

where, C_{PV_s} is the PV system capacity required and C_m is the PV module capacity.

The required number of modules wired in series (N_{PV_s}) is calculated as follows.

$$N_{PV_s} = \frac{V_s}{V_m} \tag{4}$$

where, V_s is the system voltage and V_m is the PV module voltage.

The required number of modules wired in parallel (N_{PV_p}) is calculated as follows.

$$N_{PV_p} = \frac{E_d R_{at}}{V_s S_d I_m} \tag{5}$$

where, E_d is the system daily energy required, R_{at} is the array-to-load ratio, V_s is the system voltage, S_d is the daily solar radiation and I_m is the PV module current.

The PV capacity and other technical requirements have been determined for all four scenarios described in chapter 5. The PV array sizing for the different scenarios is shown in Table 11.

Table 11: PV array sizing for the different scenarios.

Solar PV Array	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Daily energy consumption	kWh	3.7	0	3.7	7.5	14.3	0	14.3	7.5
Daily PV energy generation requirement	kWh	4.8	0	4.8	9.8	18.6	0	18.6	9.8
PV capacity required	kW	1.42	0	1.42	2.87	5.48	0	5.48	2.87
Total number of modules	Unit	6	0	6	12	22	0	22	12
Required PV modules wired in series	Unit	2	2	2	2	2	2	2	2
Pequired PV modules wired in parallel	Unit	3	0	3	6	11	0	11	6

6.2.2 Maximum power point tracker charge controller

A maximum power point tracker (MPPT) charge controller is an electronic DC to DC converter that optimizes the match between the PV array and the battery bank. To determine the size of the charge controller, the technical specification that has been considered is shown in Table 12.

Table 12: Technical specification of selected MPPT charge controller.

Technical specification - Charge Controller	
MPPT Voltage (V)	48

The maximum PV array current (I_{PV}) is calculated as follows.

$$I_{PV} = I_{m_{SC}} N_{PV_p} \tag{6}$$

where, $I_{m_{SC}}$ is the PV module short current and N_{PV_p} is the number of modules wired in parallel.

The charge controller size (S_{CC}) is calculated as follows.

$$S_{CC} = I_{PV} S_f \tag{7}$$

where, I_{PV} is the maximum PV array current and S_f is the safety factor.

The charge controller size has been determined for all four scenarios described in chapter 5. The charge controller sizing for the different scenarios is shown in Table 13.

Table 13: Charge controller sizing for the different scenarios.

Charge Controller	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Maximum PV array Isc	A	26.28	0	26.28	52.56	96.36	0	96.36	52.56
Minimum charge controller rating	A	32.72	0.00	32.72	65.44	119.97	0.00	119.97	65.44
Charge controller rating required	A	33	0	33	66	120	0	120	66

6.2.3 Battery bank

Battery storage is an essential component of off-grid PV systems. It stores the surplus energy generated by PV system and releases the energy when the demand is not met or during the night when there is no solar radiation available to be converted in energy.

For this study, lead acid batteries have been considered for the system design. The selection of this type of battery is due to its low cost compared to other types of batteries. To determine the size of the battery bank, the technical specifications that have been considered are shown in Table 14.

Table 14: Technical specifications of selected lead acid battery.

Technical specifications – Lead acid battery	
Charge Discharge efficiency (%)	0.8
Battery Voltage (V)	12
Battery Capacity (Ah)	115

The size of the battery bank is determined considering different DoD, so a DoD of 80%, 50% and 30% have been considered. The decision of selecting different DoD is particularly important to evaluate the implication of DoD in battery's lifetime (discussed in chapter 7) and total system CAPEX (discussed in chapter 8).

The daily charge requirement is calculated as follows.

$$C_D = \frac{E_d}{V_s} \tag{8}$$

where, E_d is the system daily energy required and V_s is the system voltage.

The battery system capacity required is calculated as follows.

$$C_B = \frac{C_D D_{aut}}{DoD_{max} E_b} \tag{9}$$

where, C_D is the daily charge requirement, D_{aut} is the days of autonomy of the system, DoD_{max} is the maximum selected depth of discharge of the battery and E_b is the battery's charge discharge efficiency.

The required number of batteries in a string (N_{B_s}) is calculated as follows.

$$N_{B_s} = \frac{V_s}{V_b} \tag{10}$$

where, V_s is the system voltage and V_b is the battery voltage.

The required number of parallel strings (N_{B_p}) is calculated as follows.

$$N_{B_p} = \frac{C_{B_S}}{C_b} \tag{11}$$

where, C_{B_S} is the battery system capacity and C_b is the capacity per battery.

The lead acid battery size considering a DoD of 80%, 50% and 30% has been determined for all four scenarios described in chapter 5. The battery sizing for the different scenarios is shown in Table 15, Table 16 and Table 17.

Table 15: Battery sizing with 80% DoD for the different scenarios.

Batteries - 80% DoD	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Daily energy consumption	kWh	3.718	XX	3.718	XX	14.308	XX	14.308	XX
Required battery capacity	Ah	182	XX	182	XX	699	XX	699	XX
Required battery capacity	Wh	8714	XX	8714	XX	33534	XX	33534	XX
Number of parallel strings	Unit	2	XX	2	XX	7	XX	7	XX
Number of betteries in a string	Unit	4	XX	4	XX	4	XX	4	XX
Total number of Batteries	Unit	8	XX	8	XX	28	XX	28	XX
Battery Capacity - 80% DoD	kWh	11	XX	11	XX	39	XX	39	XX

Table 16: Battery sizing with 50% DoD for the different scenarios.

Batteries - 50% DoD	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Daily energy consumption	kWh	3.7	XX	3.7	XX	14.3	XX	14.3	XX
Required battery capacity	Ah	290	XX	290	XX	1118	XX	1118	XX
Required battery capacity	Wh	13943	XX	13943	XX	53655	XX	53655	XX
Number of parallel strings	Unit	3	XX	3	XX	10	XX	10	XX
Number of betteries in a string	Unit	4	XX	4	XX	4	XX	4	XX
Total number of Batteries	Unit	12	XX	12	XX	40	XX	40	XX
Battery Capacity - 50% DoD	kWh	17	XX	17	XX	55	XX	55	XX

Table 17: Battery sizing with 30% DoD for the different scenarios.

Batteries - 30% DoD	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Daily energy consumption	kWh	3.7	XX	3.7	XX	14.3	XX	14.3	XX
Required battery capacity	Ah	484	XX	484	XX	1863	XX	1863	XX
Required battery capacity	Wh	23238	XX	23238	XX	89425	XX	89425	XX
Number of parallel strings	Unit	5	XX	5	XX	17	XX	17	XX
Number of betteries in a string	Unit	4	XX	4	XX	4	XX	4	XX
Total number of Batteries	Unit	20	XX	20	XX	68	XX	68	XX
Battery Capacity - 30% DoD	kWh	28	XX	28	XX	94	XX	94	XX

6.2.4 Inverter

Inverter is a device that converts from DC to AC. The inverter provides the power electronic interface between the DC side of the system (PV modules, battery bank and any DC appliances) and the AC side of the system (load circuits for any AC appliances. In this study the DC system voltage is 48V and the AC system voltage is 230V. To determine the size of the inverter, the technical specifications that have been considered are shown in Table 18.

Table 18: Technical specification of selected inverter.

Technical specifications - Inverter	
Oversize margin for device start-up power	3
Inverter efficiency (%)	99

The inverter size required (S_I) is calculated as follows.

$$S_I = L_p M_o S_f \tag{12}$$

where, L_p is the peak AC load, M_o is the oversize margin for device start-up power and S_f is the safety factor.

The inverter size has been determined for all four scenarios described in chapter 5. The inverter sizing for the different scenarios is shown in Table 19.

Table 19: Inverter sizing for the different scenarios.

Inverter	Units	Baseline		Baseline + Irrigation		Baseline + Mill		Baseline + Irrigation + Mill	
		System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage	System w/ battery storage	System w/ water tank storage
Maximum running power draw	kW	0.52	0.00	0.52	1.50	2.05	0.00	2.05	1.50
Minimium Inverter Rating	kW	1.96	0.00	1.96	1.88	7.70	0.00	7.70	1.88
Actual Inverter Rating	kW	2	0	2	2	8	0	8	2

6.2.5 Cable

The selection of cable, cable size and its layout are essential parts of the system design. Cables are the medium to transfer electricity from PV modules to appliances. For the cable selection is necessary to determine the conductor resistivity and the minimum cable cross-sectional area.

The conductor resistivity (ρ) at given temperature (T) is calculated as follows.

$$\rho = \rho_{ref}\left[1 + \alpha\left(T - T_{ref}\right)\right] \tag{13}$$

where, ρ_{ref} is the conductor resistivity at reference temperature T_{ref}, α is the temperature coefficient for the conductor material specified for T_{ref}. All temperatures are in °C. For this design, the conductor material is the cooper, hence $\alpha = 0.0039, \rho_{ref} = 1.68 \cdot 10^{-8}\ \Omega m, T = 30°C$ and $T_{ref} = 20°C$.

The minimum cable cross-sectional area required (A_{min}) is calculated as follows.

$$A_{min} = \frac{2 I_{max}\, \rho L}{(V_{sys} V_d)/100} \tag{14}$$

where, I_{max} is the maximum current in the line, ρ is the conductor resistivity at given temperature, L is the total line length, V_{sys} is the system voltage and V_d is the voltage drop percentage considered.

The available cables and their respective sizes are shown in Table 20.

Table 20: Available cables and respective sizes.

Available cables	Description	Size (mm^2)
Type 1	Copper single core	10
Type 2	Copper single core	16
Type 3	Copper single core	35
Type 4	Copper single core	50
Type 5	Flat 2 core + Earth	1.5
Type 6	Flat 2 core + Earth	4
Type 7	Flat 2 core + Earth	6

The cable size and length have been determined for all four scenarios described in chapter 5. The cable sizing for the different scenarios is shown in Table 21, Table 22, Table 23 and Table 24.

Table 21: Cable sizing for Baseline scenario.

Baseline	System w/ battery storage	Imax (A)	ρ (Ωm)	Line Length (m)	System Voltage (V)	Voltage drop (%)	Amin (mm2)	Amin (mm2)	Amin (mm2) allow for 10% growth	Chosen cable (type)	Length (m)
Distribution Cable (Inverter - Meter)		2.84	1.7E-08	10	230	5.00	9E-08	0.09	0.09	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	1.7E-08	20	230	5.00	1E-08	0.01	0.01	Type 5	26
	Grocery 1	0.11	1.7E-08	20	230	5.00	7E-09	0.01	0.01	Type 5	26
	Grocery 2	0.43	1.7E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Grocery 3	0.57	1.7E-08	20	230	5.00	3E-08	0.03	0.04	Type 5	26
	Barber Shop	0.52	1.7E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Video Show	0.90	1.7E-08	20	230	5.00	5E-08	0.05	0.06	Type 5	26
	Irrigation	8.15	1.7E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Mill	8.32	1.7E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	EnergyHub Monitoring	0.09	1.7E-08	20	230	5.00	6E-09	0.01	0.01	Type 5	26
PV Modules Cable (PV Module - PV Module)		10.95	1.7E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		30.90	1.7E-08	8	60.68	3.00	5E-06	4.74	-	Type 1	24
Charge Controller Cable (Charge Controller - Battery)		41.56	1.7E-08	5	45.12	3.00	5E-06	5.36	-	Type 1	10
Battery Cable (Battery - Inverter)		10.88	1.7E-08	3	48	1.00	2E-06	2.37	-	Type 1	6

Table 22: Cable sizing for Baseline + Irrigation scenario.

Baseline + Irrigation	System w/ battery storage	Imax (A)	ρ (Ωm)	Line Length (m)	System Voltage (V)	Voltage drop (%)	Amin (mm2)	Amin (mm2)	Amin (mm2) allow for 10% growth	Chosen cable (type)	Length (m)
Distribution Cable (Inverter - Meter)		2.84	2E-08	10	230	5.00	9E-08	0.09	0.09	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	2E-08	20	230	5.00	1E-08	0.01	0.01	Type 5	26
	Grocery 1	0.11	2E-08	20	230	5.00	7E-09	0.01	0.01	Type 5	26
	Grocery 2	0.43	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Grocery 3	0.57	2E-08	20	230	5.00	3E-08	0.03	0.04	Type 5	26
	Barber Shop	0.52	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Video Show	0.90	2E-08	20	230	5.00	5E-08	0.05	0.06	Type 5	26
	Irrigation	8.15	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Mill	8.32	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	EnergyHub Monitoring	0.09	2E-08	20	230	5.00	6E-09	0.01	0.01	Type 5	26
PV Modules Cable (PV Module - PV Module)		10.95	2E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		30.90	2E-08	8	60.68	3.00	5E-06	4.74	-	Type 1	24
Charge Controller Cable (Charge Controller - Battery)		41.56	2E-08	5	45.12	3.00	5E-06	5.36	-	Type 1	10
Battery Cable (Battery - Inverter)		10.88	2E-08	3	48	1.00	2E-06	2.37	-	Type 1	6
Baseline + Irrigation	**System w/ water tank storage**	**Imax (A)**	**ρ (Ωm)**	**Line Length (m)**	**System Voltage (V)**	**Voltage drop (%)**	**Amin (mm2)**	**Amin (mm2)**	**Amin (mm2) allow for 10% growth**	**Chosen cable (type)**	**Length (m)**
Distribution Cable (Inverter - Meter)		8.15	2E-08	10	230	5.00	2E-07	0.25	0.27	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 1	0.11	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 2	0.43	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 3	0.57	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Barber Shop	0.52	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Video Show	0.90	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Irrigation	8.15	2E-08	100	230	5.00	2E-06	2.47	2.72	Type 6	130
	Mill	8.32	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	EnergyHub Monitoring	0.09	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
PV Modules Cable (PV Module - PV Module)		10.95	2E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		61.80	2E-08	8	60.68	3.00	9E-06	9.48	-	Type 1	48
Charge Controller Cable (Charge Controller - Inverter)		61.80	2E-08	5	60.68	3.00	6E-06	5.93	-	Type 1	10

Table 23: Cable sizing for Baseline + Mill scenario.

Baseline + Mill	System w/ battery storage	Imax (A)	ρ (Ωm)	Line Length (m)	System Voltage (V)	Voltage drop (%)	Amin (mm2)	Amin (mm2)	Amin (mm2) allow for 10% growth	Chosen cable (type)	Length (m)
Distribution Cable (Inverter - Meter)		11.15	2E-08	10	230	5.00	3E-07	0.34	0.37	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	2E-08	20	230	5.00	1E-08	0.01	0.01	Type 5	26
	Grocery 1	0.11	2E-08	20	230	5.00	7E-09	0.01	0.01	Type 5	26
	Grocery 2	0.43	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Grocery 3	0.57	2E-08	20	230	5.00	3E-08	0.03	0.04	Type 5	26
	Barber Shop	0.52	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Video Show	0.90	2E-08	20	230	5.00	5E-08	0.05	0.06	Type 5	26
	Irrigation	8.15	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Mill	8.32	2E-08	20	230	5.00	5E-07	0.50	0.56	Type 5	26
	EnergyHub Monitoring	0.09	2E-08	20	230	5.00	6E-09	0.01	0.01	Type 5	26
PV Modules Cable (PV Module - PV Module)		10.95	2E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		113.30	2E-08	8	60.68	3.00	2E-05	17.38	-	Type 3	88
Charge Controller Cable (Charge Controller - Battery)		152.37	2E-08	5	45.12	3.00	2E-05	19.65	-	Type 3	10
Battery Cable (Battery - Inverter)		42.75	2E-08	3	48	1.00	9E-06	9.33	-	Type 1	6

Table 24: Cable sizing for Baseline + Mill + Irrigation scenario.

Baseline + Irrigation + Mill	System w/ battery storage	Imax (A)	ρ (Ωm)	Line Length (m)	System Voltage (V)	Voltage drop (%)	Amin (mm2)	Amin (mm2)	Amin (mm2) allow for 10% growth	Chosen cable (type)	Length (m)
Distribution Cable (Inverter - Meter)		11.15	2E-08	10	230	5.00	3E-07	0.34	0.37	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	2E-08	20	230	5.00	1E-08	0.01	0.01	Type 5	26
	Grocery 1	0.11	2E-08	20	230	5.00	7E-09	0.01	0.01	Type 5	26
	Grocery 2	0.43	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Grocery 3	0.57	2E-08	20	230	5.00	3E-08	0.03	0.04	Type 5	26
	Barber Shop	0.52	2E-08	20	230	5.00	3E-08	0.03	0.03	Type 5	26
	Video Show	0.90	2E-08	20	230	5.00	5E-08	0.05	0.06	Type 5	26
	Irrigation	8.15	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Mill	8.32	2E-08	20	230	5.00	5E-07	0.50	0.56	Type 5	26
	EnergyHub Monitoring	0.09	2E-08	20	230	5.00	6E-09	0.01	0.01	Type 5	26
PV Modules Cable (PV Module - PV Module)		10.95	2E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		113.30	2E-08	8	60.68	3.00	2E-05	17.38	-	Type 3	88
Charge Controller Cable (Charge Controller - Battery)		152.37	2E-08	5	45.12	3.00	2E-05	19.65	-	Type 3	10
Battery Cable (Battery - Inverter)		42.75	2E-08	3	48	1.00	9E-06	9.33	-	Type 1	6
Baseline + Irrigation + Mill	**System w/ water tank storage**	**Imax (A)**	**ρ (Ωm)**	**Line Length (m)**	**System Voltage (V)**	**Voltage drop (%)**	**Amin (mm2)**	**Amin (mm2)**	**Amin (mm2) allow for 10% growth**	**Chosen cable (type)**	**Length (m)**
Distribution Cable (Inverter - Meter)		8.15	2E-08	10	230	5.00	2E-07	0.25	0.27	Type 5	13
Supply Cable (Meter - Socket)	Phone Charging	0.22	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 1	0.11	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 2	0.43	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Grocery 3	0.57	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Barber Shop	0.52	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Video Show	0.90	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	Irrigation	8.15	2E-08	100	230	5.00	2E-06	2.47	2.72	Type 6	130
	Mill	8.32	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
	EnergyHub Monitoring	0.09	2E-08	0	230	5.00	0	0.00	0.00	Type 5	0
PV Modules Cable (PV Module - PV Module)		0.00	2E-08	0	30.34	3.00	0	0.00	-	Type 1	0
PV Array Cable (PV Array - Charge Controller)		61.80	2E-08	8	60.68	3.00	9E-06	9.48	-	Type 1	48
Charge Controller Cable (Charge Controller - Inverter)		61.80	2E-08	5	60.68	3.00	6E-06	5.93	-	Type 1	10

7 Component lifetime

The lifetime of a component is the period of time during which the component is expected to function within its specified manufacturing parameters. The correct determination of the component lifetime is extremely important as it defines when a component needs to be replaced and the depreciation of the component along the years.

In this study, the main system is composed by PV modules, charge controller, battery bank and inverter. Other components that give support to the main system are also considered such as cables, meters, protection components, infrastructure and equipment.

The determination of the lifetime for all components, except battery lifetime, was based in a study carried out by the National Renewable Energy Laboratory (NREL). This study modelled representative systems in SSA and can be considered as a reliable source to give indicative data regarding lifetime of components [34].

The battery lifetime has been determined according to an equation that combines two parameters to estimate the battery's total lifetime. This equation was developed by the author.

7.1 PV modules

The PV module warranty typically varies between 15 and 30 years depending on the manufacture. The NREL study indicates a lifetime of 20 years for PV modules, so the same value has been considered in this study.

7.2 Charge controller

The MPPT charge controller warranty typically varies between 15 and 20 years depending on the manufacture. The NREL study indicates a lifetime of 20 years for MPPT charge controllers, so the same value has been considered in this study.

7.3 Battery lifetime

There are many factors that influence the lifetime of lead acid batteries such as depth of discharge, rate of discharge, temperature and humidity [35, 36, 37, 38]. In this study, only the influence of depth of discharge and temperature have been considered. Higher depths of discharge and elevated temperatures reduce the battery's lifetime. Thus, an equation that combines both parameters was developed to estimate the battery's total lifetime (Lf_{tot}), as follows.

$$Lf_{tot} = \frac{C_{rated}}{\sum_{i=1}^{year} C_{real_i}} \tag{15}$$

where, C_{rated} is the battery's rated number of cycles according to manufacture specifications and C_{real} is the battery's monthly total cycles. Hence, the yearly sum is calculated for twelve different C_{real}, one for each month, being calculated as:

$$C_{real} = \frac{\sum_{i=1}^{month} L_{f_i}}{T_{deg}} \tag{16}$$

where, L_f is the life fraction for each maximum DoD of each day and T_{deg} is the temperature degradation as in Table 25. Hence, the monthly sum is calculated for each month duration (28, 30 or 31 days) and using Table 26 for the maximum DoD of each day.

Table 25: Temperature degradation according to Arrhenius equation.

Temperature (°C)	Expected Life (%)	Tdeg
20	100	1
21	90	0.9
22	86	0.86
23	82	0.82
24	84	0.84
25	70	0.7
26	64	0.64
27	60	0.6
28	56	0.56
29	54	0.54
30	50	0.5
31	44	0.44
32	41	0.41
33	38	0.38
34	35	0.35
35	32	0.32

The temperature degradation was determined based on the monthly average temperature (T_{avg}) data for Malawi. The data was extracted from NASA's SSE model.

Table 26: Battery's life fraction according to different DoD.

DoD	Life Cycle	Life Fraction
10	5000	1.00
15	4000	1.25
20	3400	1.47
25	2100	2.38
30	1800	2.78
35	1600	3.13
40	1500	3.33
45	1200	4.17
50	1000	5.00
55	900	5.56
60	800	6.25
65	700	7.14
70	650	7.69
75	600	8.33
80	550	9.09
85	500	10.00
90	450	11.11
95	400	12.50

The hourly battery's DoD was determined based on simulation results using HOMER Pro (Hybrid Optimization Model for Electric Renewables) software. HOMER Pro simulates the system operation by calculating different parameters (PV output, battery's state of charge, unmet load and others) on an hourly basis over the entire year. The output allows the user to analyse the system operation and reliability of the system design. All data regarding system component inputted in HOMER Pro is based on assumptions and sizes determined in chapter 6.

The maximum DoD of each day (DoD_{max}) is calculated as follows.

$$DoD_{max} = 1 - SoC_{min} \tag{17}$$

where, SoC_{min} is the minimum battery's state of charge.

An example of the identification of the maximum DoD of one day randomly selected is illustrated in Figure 17.

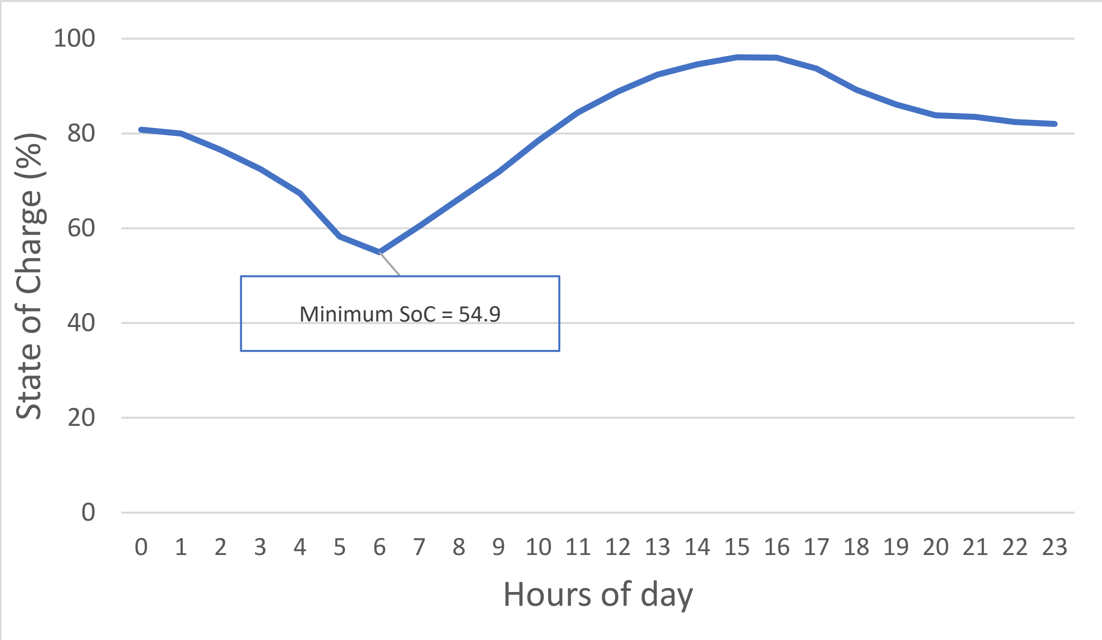

Figure 17: Example of the identification of the maximum DoD of the day.

The steps taken to calculate the total battery's lifetime are shown in Table 27. In this case, the Baseline and Baseline + Irrigation scenarios with battery allowing a maximum DoD of 80% was selected as an example.

Table 27: Lifetime of battery allowing maximum DoD of 80% for Baseline and Baseline + Irrigation scenarios.

Month	$\sum L_f$	T_{avg}	T_{deg}	C_{real}
January	101.1	24	0.84	120.4
February	65.3	23	0.82	79.7
March	90.1	23	0.82	109.9
April	55.0	22	0.86	63.9
May	64.8	21	0.9	72.0
June	72.7	19	1	72.7
July	63.9	19	1	63.9
August	75.4	21	0.9	83.7
September	52.4	25	0.7	74.9
October	52.2	26	0.64	81.5
November	76.8	26	0.64	120.0
December	110.2	24	0.84	131.2
Year Sum				**1073.9**
Total Lifetime in years (Lf_{tot})				**4.7**

The calculation of the total battery's lifetime for the other scenarios were performed following the same steps described above. The results of battery's lifetime for the other scenarios are shown in Table 28.

Table 28: Results of battery's lifetime for the different scenarios.

Scenarios	Maximum DoD of battery (%)	Total battery's lifetime (years)
Baseline Baseline + Irrigation	80	4.7
	50	6.8
	30	9.2
Baseline +Mill Baseline + Mill + Irrigation	80	4.8
	50	7.3
	30	9.1

7.4 Inverter

The inverter warranty typically varies between 8 and 15 years depending on the manufacture. The NREL study indicates a lifetime of 10 years for inverters, so the same value has been considered in this study.

7.5 Other components

For the other components of the system such as cables, meters, protection components, infrastructure and equipment, the NREL study indicates a component's lifetime equivalent to the project's lifetime. In this study, the project's lifetime is 20 years, so the same value has been considered.

8 Capital Cost

CAPEX is the total upfront costs required at the beginning of a project to start the operation of the system. In this study, the CAPEX is divided in ten sections which are generation, storage, conversion, distribution, protection, metering, installation, infrastructure, equipment and project development.

All the data related to costs was accessed through consultation with UoS E4D team and CEM and represents real project costs based on quotes from reputable suppliers in Malawi. Costs for components of the generation, storage, conversion and protection systems were obtained from the supplier Solair, Sonlite and Fortune CP. Costs for components of the distribution system (wiring) were obtained from Cable Manufactures Ltd. Costs for metering equipment were obtained from Sparkmeter. The system's installation cost was obtained from Sonlite. The system's infrastructure cost was obtained from Eckali Building Contractors. Equipment costs that include the costs of all appliances described in chapter 4 were obtained from CEM and supplier FISD. Finally, the project development costs that include feasibility study, community training and project management are calculated as $833 per kW installed based on a World Bank study [39].

The total CAPEX is then, allocated to the PUE types that compose the Energy Hub using the following method.

1. The costs related to metering, installation and project development are distributed equally across all PUE types.
2. The costs related to infrastructure and equipment are allocated individually to each PUE type.
3. The costs related to generation, storage, conversion, distribution and protection are distributed according to the energy consumption of each PUE type.

The CAPEX value by PUE type for generation, storage, conversion, distribution, protection, infrastructure and equipment (CP_{PUE}) is calculated as follows.

$$CP_{PUE} = \frac{CP_{total}E_{PUE}}{E_{total}} \tag{18}$$

where, CP_{total} is the total system's CAPEX, E_{PUE} is the energy consumption of each PUE type and E_{total} is the total energy consumption of the Energy Hub. Hence, the process is repeated CAPEX section.

A summary of total CAPEX for all four different scenarios considering the battery sizing with DoD of 80%, 50% and 30% along with figures showing the costs breakdown of the CAPEX values by PUE type according to equation 18 are shown in the next sections.

8.1 Baseline scenario

The baseline scenario is composed by six PUE types, where all share the system with battery storage. A summary of total system CAPEX considering the battery sizing with DoD of 80%, 50% and 30% is shown in Table 29.

Table 29: Total CAPEX considering the battery sizing with the different DoD for baseline scenario.

EnergyHub		
Summary	**System w/ battery storage**	**System w/ water tank storage**
Number os customers	6	0
System daily energy (kWh)	3.52	0
System capacity installed (kW)	1.5	0
Generation - PV and MPPT	$ 1,899.48	
Storage - Battery 80% DoD ($)	$ 2,887.32	
Storage - Battery 50% DoD ($)	$ 4,327.32	
Storage - Battery 30% DoD ($)	$ 7,207.32	
Conversion - Inverter ($)	$ 1,150.00	
Distribution - Cables and Breakers ($)	$ 404.70	
Protection - AC and DC ($)	$ 967.50	
Metering - Meter Base Station ($)	$ 1,792.00	
Installation ($)	$ 1,500.00	
Building Infrastructure ($)	$ 10,058.50	
Equipment ($)	$ 867.00	
Project Development ($)	$ 1,249.50	
Total CAPEX - Battery 80% DoD ($)	$ 22,776.00	
Total CAPEX - Battery 50% DoD ($)	$ 24,216.00	
Total CAPEX - Battery 30% DoD ($)	$ 27,096.00	

The costs breakdown of the CAPEX values by PUE type considering the battery sizing with DoD of 80% for the baseline scenario is presented in Figure 18.

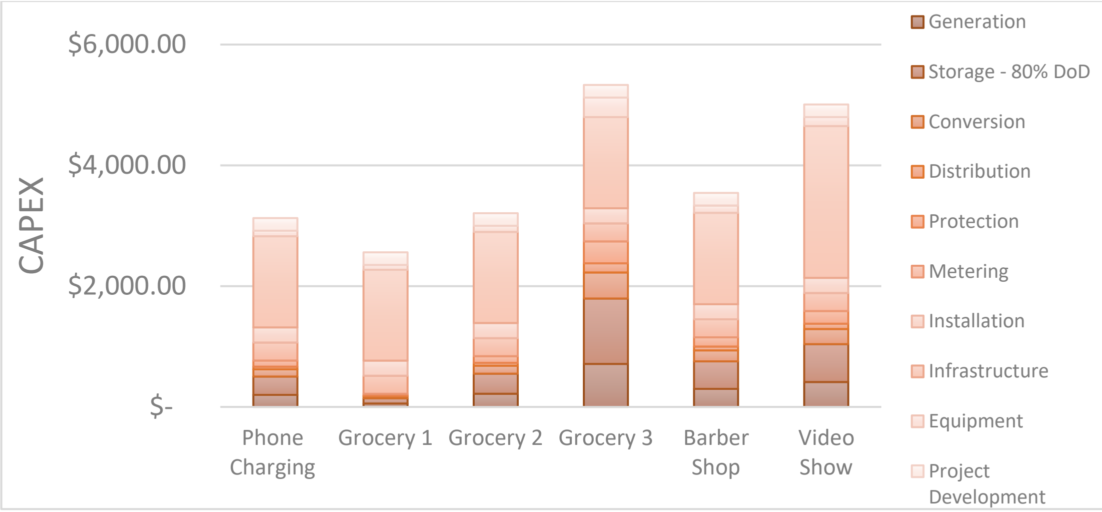

Figure 18: Costs breakdown of the CAPEX by PUE type considering the battery sizing with DoD of 80% for the baseline scenario.

8.2 Baseline + Irrigation scenario

The baseline + irrigation scenario is composed by seven PUE types, where six PUE types share a system with battery storage and one PUE type (irrigation) have a system without battery storage. A summary of total system CAPEX considering the battery sizing with DoD of 80%, 50% and 30% is shown in Table 30.

Table 30: Total CAPEX considering the battery sizing with the different DoD for baseline + irrigation scenario.

EnergyHub		
Summary	**System w/ battery storage**	**System w/ water tank storage**
Number os customers	6	1
System daily energy (kWh)	3.52	7.5
System capacity installed (kW)	1.5	3
Generation - PV and MPPT	$ 1,899.48	$ 3,551.60
Storage - Battery 80% DoD ($)	$ 2,887.32	$ -
Storage - Battery 50% DoD ($)	$ 4,327.32	$ -
Storage - Battery 30% DoD ($)	$ 7,207.32	$ -
Conversion - Inverter ($)	$ 1,150.00	$ 1,150.00
Distribution - Cables and Breakers ($)	$ 404.70	$ 380.10
Protection - AC and DC ($)	$ 967.50	$ 1,935.00
Metering - Meter Base Station ($)	$ 1,824.00	
Installation ($)	$ 5,500.00	
Building Infrastructure ($)	$ 18,629.00	
Equipment ($)	$ 9,867.00	
Project Development ($)	$ 3,748.50	
Total CAPEX - Battery 80% DoD ($)	$ 53,894.20	
Total CAPEX - Battery 50% DoD ($)	$ 55,334.20	
Total CAPEX - Battery 30% DoD ($)	$ 58,214.20	

The costs breakdown of the CAPEX values by PUE type considering the battery sizing with DoD of 50% for the baseline + irrigation scenario is presented in Figure 19.

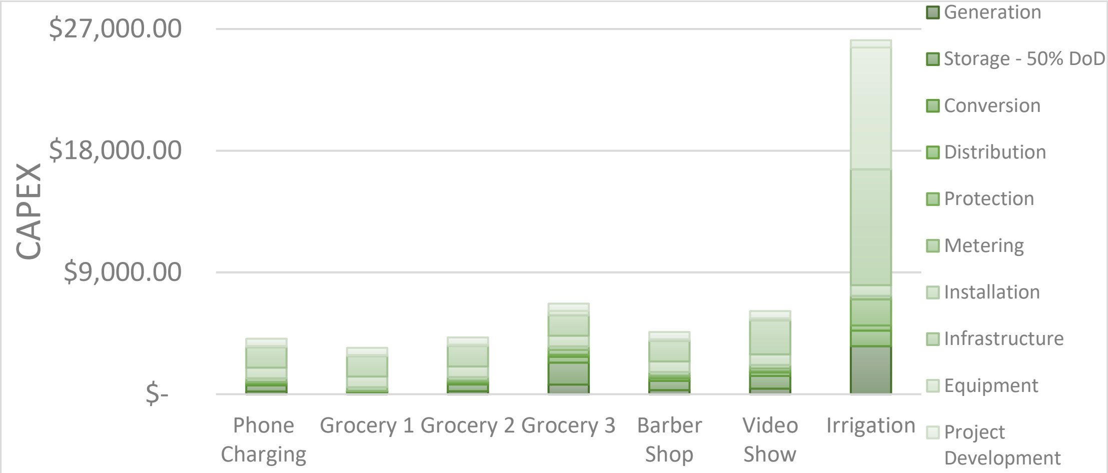

Figure 19: Costs breakdown of the CAPEX by PUE type considering the battery sizing with DoD of 50% for the baseline + irrigation scenario.

8.3 Baseline + Mill scenario

The baseline + mill scenario is composed by seven PUE types, where all share the system with battery storage. A summary of total system CAPEX considering the battery sizing with DoD of 80%, 50% and 30% is shown in Table 31.

Table 31: Total CAPEX considering the battery sizing with the different DoD for baseline + mill scenario.

EnergyHub		
Summary	**System w/ battery storage**	**System w/ water tank storage**
Number os customers	7	0
System daily energy (kWh)	14.11	0
System capacity installed (kW)	5.5	0
Generation - PV and MPPT	$	6,745.40
Storage - Battery 80% DoD ($)	$	10,090.80
Storage - Battery 50% DoD ($)	$	14,410.80
Storage - Battery 30% DoD ($)	$	24,490.80
Conversion - Inverter ($)	$	4,010.00
Distribution - Cables and Breakers ($)	$	467.86
Protection - AC and DC ($)	$	3,547.50
Metering - Meter Base Station ($)	$	1,824.00
Installation ($)	$	5,500.00
Building Infrastructure ($)	$	12,563.00
Equipment ($)	$	9,888.00
Project Development ($)	$	4,581.50
Total CAPEX - Battery 80% DoD ($)	$	59,218.06
Total CAPEX - Battery 50% DoD ($)	$	63,538.06
Total CAPEX - Battery 30% DoD ($)	$	73,618.06

The costs breakdown of the CAPEX values by PUE type considering the battery sizing with DoD of 30% for the baseline + mill scenario is presented in Figure 20.

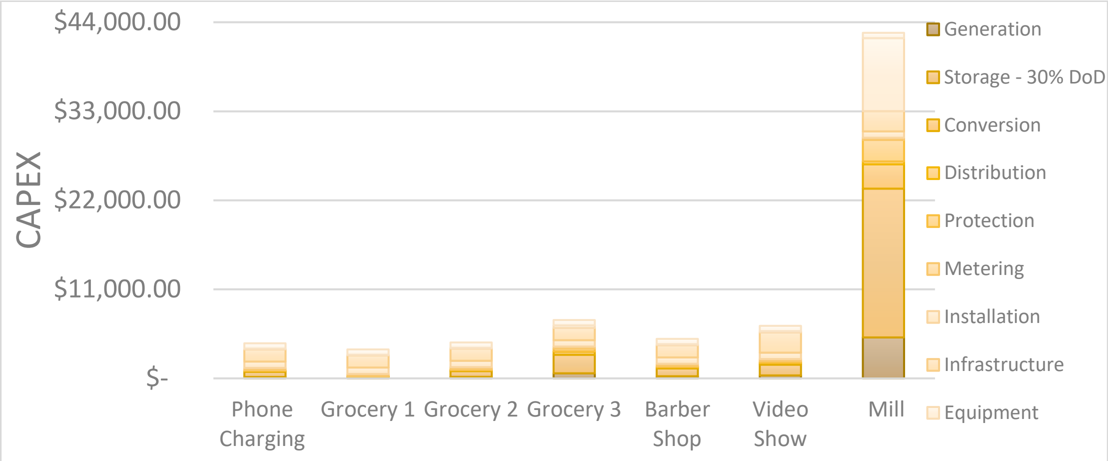

Figure 20: Costs breakdown of the CAPEX by PUE type considering the battery sizing with DoD of 30% for the baseline + mill scenario.

8.4 Baseline + Irrigation + Mill scenario

The baseline + irrigation + mill scenario is composed by eight PUE types, where seven PUE types share a system with battery storage and one PUE type (irrigation) have a system without battery storage. A summary of total system CAPEX considering the battery sizing with DoD of 80%, 50% and 30% is shown in Table 32.

Table 32: Total CAPEX considering the battery sizing with the different DoD for baseline + irrigation + mill scenario.

EnergyHub		
Summary	**System w/ battery storage**	**System w/ water tank storage**
Number os customers	7	1
System daily energy (kWh)	14.11	7.5
System capacity installed (kW)	5.5	3
Generation - PV and MPPT	$ 6,745.40	$ 3,551.60
Storage - Battery 80% DoD ($)	$ 10,090.80	$ -
Storage - Battery 50% DoD ($)	$ 14,410.80	$ -
Storage - Battery 30% DoD ($)	$ 24,490.80	$ -
Conversion - Inverter ($)	$ 4,010.00	$ 1,150.00
Distribution - Cables and Breakers ($)	$ 467.86	$ 380.10
Protection - AC and DC ($)	$ 3,547.50	$ 1,935.00
Metering - Meter Base Station ($)	$ 1,856.00	
Installation ($)	$ 9,500.00	
Building Infrastructure ($)	$ 20,674.25	
Equipment ($)	$ 18,888.00	
Project Development ($)	$ 7,080.50	
Total CAPEX - Battery 80% DoD ($)	$ 89,877.01	
Total CAPEX - Battery 50% DoD ($)	$ 94,197.01	
Total CAPEX - Battery 30% DoD ($)	$ 104,277.01	

The costs breakdown of the CAPEX values by PUE type considering the battery sizing with DoD of 80% for the baseline + irrigation + mill scenario is presented in Figure 21.

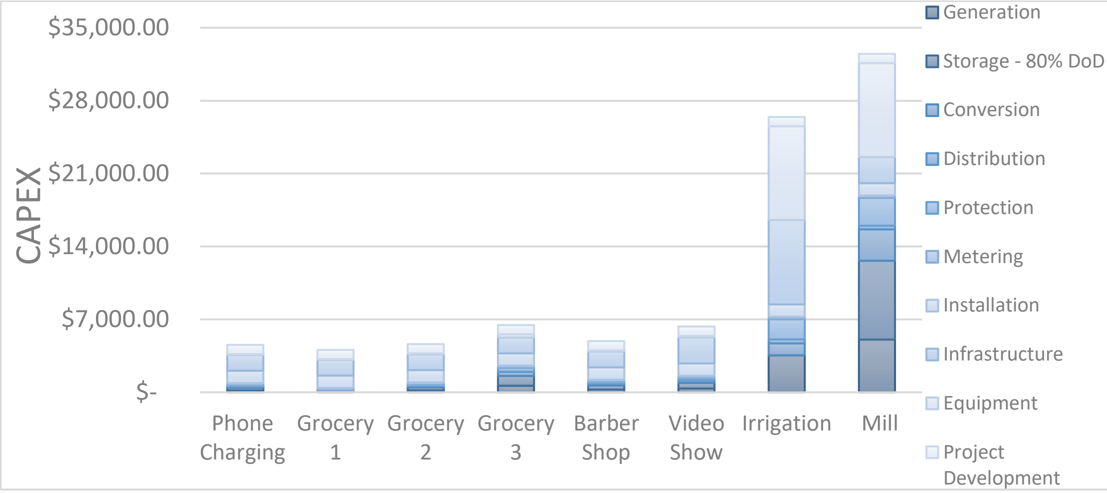

Figure 21: Costs breakdown of the CAPEX by PUE type considering the battery sizing with DoD of 80% for the baseline + irrigation + mill scenario.

9 Operational Cost

OPEX is accrued yearly and includes all incurred costs during the operation of the system to keep it functioning throughout its lifetime. In this study, the OPEX is divided in three sections which are metering fees, generation/distribution maintenance and fixed costs. It is important to mention that replacement costs are not included in the OPEX. The costs related to component's replacement will be included further in the cash flow financial statement that will be presented in chapter 11.

Metering fees per month were obtained from the supplier Sparkmeter and generation/distribution maintenance costs were obtained from benchmarks values of an NREL study [34] that determined the cost at 2% of CAPEX.

In this study, the maintenance cost has been considered the same for systems with battery sizing with the different DoD considered, as the size of the battery bank does not influence the incurred costs during the operation of the system. Therefore, the total maintenance cost for each scenario (C_{mtn}) is calculated as follows.

$$C_{mtn} = 0.02\left(\prod_{i=1}^{N} CP_{total_i}\right)^{1/N} \qquad (19)$$

where, CP_{total} is the total CAPEX for the scenario considered and N is the different battery's DoD considered in each scenario. Hence, the nth root of the product of CP_{total} for each DoD considered (80, 50 and 30%) is calculated.

Fixed costs include land rental and labour. Land rental costs were obtained from UP's Sustainable Energy Management Unit that provided estimated costs between \$20 - \$40 per month based on previous solar PV project deployed in rural village. The lower value was used for all scenarios as the size of the land does not change radically. Labour costs were also obtained from benchmarks values of an NREL study [34] that determined the labour cost of \$3,000 per year for a 100-customer grid. This value was scaled down to fit the characteristics of this study.

License fees have not been included on the OPEX calculations, as a recent stakeholder engagement suggests that systems with an installed capacity below 100kW will be exempt from licensing [40]. A summary of total OPEX for all four different scenarios considered is presented in the next sections.

9.1 Baseline scenario

The summary of total OPEX with breakdown costs for the baseline scenario is presented in Table 33.

Table 33: OPEX summary for the baseline scenario.

Baseline	**Metering**	
	Fee per user per month	$0.20
	Number of entrepreneurs	6
	TOTAL ANNUAL* METERING *FEES	***$14***
	Generation and Distribution Maintenance	
	Fixed Fee (% of CAPEX)	2%
	TOTAL MAINTENANCE COSTS	***$493***
	Fixed	
	Land Rental	$240
	Labour	$200
	TOTAL FIXED COSTS	***$440***
	TOTAL BASELINE OPEX	***$947***

9.2 Baseline + Irrigation scenario

The summary of total OPEX with breakdown costs for the baseline + irrigation scenario is presented in Table 34.

Table 34: OPEX summary for the baseline + irrigation scenario.

Baseline + Irrigation	**Metering**	
	Fee per user per month	$0.20
	Number of entrepreneurs	7
	TOTAL ANNUAL METERING FEES	***$17***
	Generation and Distribution Maintenance	
	Fixed Fee (% of CAPEX)	2%
	TOTAL MAINTENANCE COSTS	***$1,116***
	Fixed	
	Land Rental	$360
	Labour	$400
	TOTAL FIXED COSTS	***$760***
	TOTAL BASELINE + IRRIGATION OPEX	***$1,893***

9.3 Baseline + Mill scenario

The summary of total OPEX with breakdown costs for the baseline + mill scenario is presented in Table 35.

Table 35: OPEX summary for the baseline + mill scenario.

Baseline + Mill	**Metering**	
	Fee per user per month	$0.20
	Number of entrepreneurs	7
	TOTAL ANNUAL METERING FEES	***$17***
	Generation and Distribution Maintenance	
	Fixed Fee (% of CAPEX)	2%
	TOTAL MAINTENANCE COSTS	***$1,304***
	Fixed	
	Land Rental	$240
	Labour	$250
	TOTAL FIXED COSTS	***$490***
	TOTAL BASELINE + MILL OPEX	***$1,811***

9.4 Baseline + Irrigation + Mill scenario

The summary of total OPEX with breakdown costs for the baseline + irrigation + mill scenario is presented in Table 36.

Table 36: OPEX summary for the baseline + irrigation + mill scenario.

Baseline + Irrigation + Mill	**Metering**	
	Fee per user per month	$0.20
	Number of entrepreneurs	8
	TOTAL ANNUAL METERING FEES	***$19***
	Generation and Distribution Maintenance	
	Fixed Fee (% of CAPEX)	2%
	TOTAL MAINTENANCE COSTS	***$1,919***
	Fixed	
	Land Rental	$360
	Labour	$450
	TOTAL FIXED COSTS	***$810***
	TOTAL BASELINE + IRRIGATION + MILL OPEX	***$2,748***

10 Financing Energy Hub projects

The funding structure is a model in which an Energy Hub entrepreneur pays a deposit according to the PUE type and a recurring fee at monthly intervals during the whole lifetime of the system to have the right to run a business in the Energy Hub. The monthly fee is calculated to match the ability to pay of the Energy Hub entrepreneurs considering the monthly income of each PUE type included in the Energy Hub.

The financing model is based on a single micro-energy provider who ensures the supply, maintenance and replacement of components of the off-grid PV system during the lifetime of the project as displayed in Figure 22.

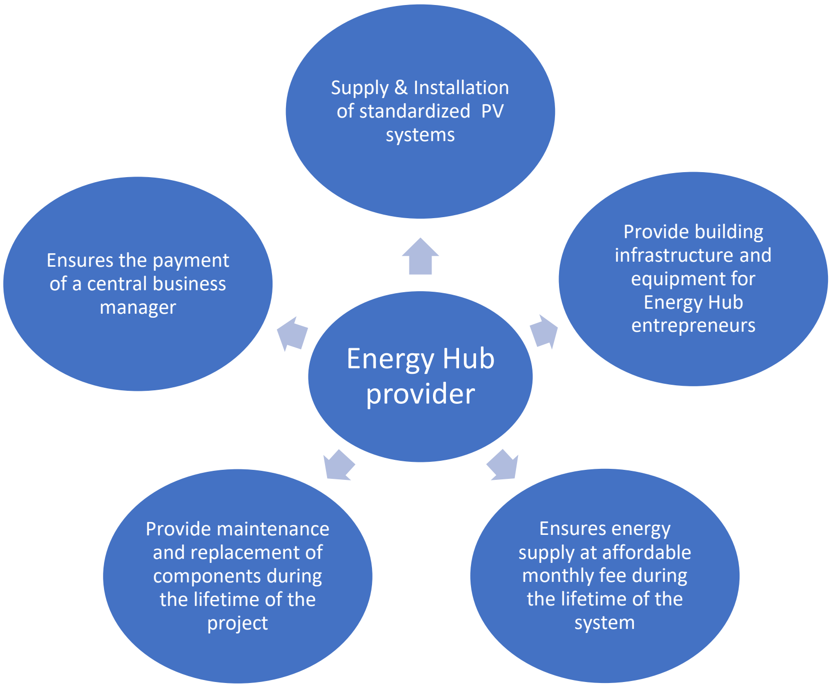

Figure 22: Energy Hub financing model.

The deposit (D), which is the upfront cost paid by each entrepreneur according to each PUE type is calculated as follows:

$$D = D_{\%} L_n \tag{20}$$

where, $D_{\%}$ is the percentage selected for the deposit and L_n is the total loan amount issued to an entrepreneur, being calculated as:

$$L_n = CP_{PUE}(1 + A_r) \tag{21}$$

where, $CP_{PUE\,total}$ is the total capital cost for each PUE type (determined in chapter 8) and A_r is the arrangement fee, being calculated as:

$$A_r = A_{\%}CP_{PUE} \quad (22)$$

where, $A_{\%}$ is the percentage selected for the arrangement fee.

The monthly collection fee (F_{month}) for each PUE type to keep the Energy Hub running is calculated as follows.

$$F_{month} = \frac{(L_n - D)(r/12)}{[1 - (1 + r/12)^{-n}]} \quad (23)$$

where, L_n is the total loan amount issued to an entrepreneur, D is the deposit, r is the interest rate, n is the number of monthly payments. For this model, $D_{\%}$ = 10%, $A_{\%}$ = 3%, r = 5% and n = 240 which is equivalent to system lifetime (20 years).

A summary of total monthly fee for each PUE type included in the different scenarios considered is presented in the next sections.

10.1 Baseline scenario

A summary of total monthly fee for each PUE type included in the baseline scenario is presented in Table 37.

Table 37: Summary of monthly fee for each PUE type included in the baseline scenario.

PUE Type	Monthly fee (F_{month}): System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Phone Charging	$ 19.13	$ 20.05	$ 21.91
Grocery 1	$ 15.66	$ 15.92	$ 16.45
Grocery 2	$ 19.62	$ 20.64	$ 22.66
Grocery 3	$ 32.61	$ 35.92	$ 42.52
Barber Shop	$ 21.68	$ 23.07	$ 25.84
Video Show	$ 30.64	$ 32.55	$ 36.38

10.2 Baseline + Irrigation scenario

A summary of total monthly fee for each PUE type included in the baseline + irrigation scenario is presented in Table 38.

Table 38: Summary of monthly fee for each PUE type included in the baseline + irrigation scenario.

Monthly fee (F_{month})

PUE Type	System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Phone Charging	$ 24.17	$ 25.10	$ 26.95
Grocery 1	$ 20.71	$ 20.97	$ 21.50
Grocery 2	$ 24.67	$ 25.68	$ 27.71
Grocery 3	$ 37.66	$ 40.96	$ 47.57
Barber Shop	$ 26.72	$ 28.11	$ 30.89
Video Show	$ 35.68	$ 37.60	$ 41.43
Irrigation	$ 16.01	$ 16.01	$ 16.01

10.3 Baseline + Mill scenario

A summary of total monthly fee for each PUE type included in the baseline + mill scenario is presented in Table 39.

Table 39: Summary of monthly fee for each PUE type included in the baseline + mill scenario.

Monthly fee (F_{month})

PUE Type	System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Phone Charging	$ 24.19	$ 24.88	$ 26.50
Grocery 1	$ 21.23	$ 21.43	$ 21.89
Grocery 2	$ 24.62	$ 25.38	$ 27.15
Grocery 3	$ 35.85	$ 38.32	$ 44.09
Barber Shop	$ 26.38	$ 27.42	$ 29.85
Video Show	$ 34.94	$ 36.37	$ 39.72
Mill	$ 195.07	$ 214.91	$ 261.19

10.4 Baseline + Irrigation + Mill scenario

A summary of total monthly fee for each PUE type included in the baseline + irrigation + mill scenario is presented in Table 40.

Table 40: Summary of monthly fee for each PUE type included in the baseline + irrigation + mill scenario.

Monthly fee (F_{month})

PUE Type	System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Phone Charging	$ 27.88	$ 28.58	$ 30.19
Grocery 1	$ 24.93	$ 25.12	$ 25.58
Grocery 2	$ 28.31	$ 29.07	$ 30.84
Grocery 3	$ 39.54	$ 42.01	$ 47.78
Barber Shop	$ 30.08	$ 31.12	$ 33.54
Video Show	$ 38.63	$ 40.07	$ 43.41
Irrigation	$ 16.17	$ 16.17	$ 16.17
Mill	$ 198.76	$ 218.60	$ 264.88

11 Financial statements

The final part of the tool was designed to evaluate the economic viability of the deployment of Energy Hubs. The viability is determined through the outcomes of two key financial statements, which are income statement and cash flow. Figure 23 presents an example of the financial statement for the system with battery sizing considering 50% for the baseline + irrigation scenario for the first ten years of the lifetime of the project.

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
INCOME STATEMENT											
Revenues											
Deposit		$28,497	$0	$0	$0	$0	$0	$0	$0	$0	$0
Montly payment		$20,311	$21,936	$23,691	$25,586	$27,633	$29,844	$32,232	$34,810.14	$37,595	$40,603
Real monthly payment		$19,296	$20,839	$22,507	$24,307	$26,252	$28,352	$30,620	$33,070	$35,715	$38,572
Revenue Stream		$47,793	$20,839	$22,507	$24,307	$26,252	$28,352	$30,620	$33,070	$35,715	$38,572
Total Costs											
Operating Costs		$9,463	$9,767	$10,095	$10,449	$10,832	$11,246	$11,693	$12,175	$12,696	$13,259
Replacement Cost - Battery		$0	$0	$0	$0	$0	$0	$21,600	$0	$0	$0
Replacement Cost - Inverter		$0	$0	$0	$0	$0	$0	$0	$0	$0	$11,500
CEM Management		$8,000	$8,640	$9,331	$10,078	$10,884	$11,755	$12,695	$13,711	$14,807	$15,992
Cost Stream		$17,463	$18,407	$19,426	$20,527	$21,716	$23,001	$45,988	$25,886	$27,504	$40,751
EBITDA		$30,330	$2,433	$3,081	$3,780	$4,535	$5,351	-$15,368	$7,184	$8,212	-$2,178
Depreciation		$2,581	$2,581	$2,581	$2,581	$2,581	$2,581	$2,581	$2,581	$2,581	$2,581
EBIT and EBT		$27,750	-$148	$500	$1,199	$1,955	$2,771	-$17,948	$4,603	$5,631	-$4,759
FINANCE											
Tax		$8,325	$0	$150	$360	$586	$831	$0	$1,381	$1,689	$0
Annual Net Income		$19,425	-$148	$350	$840	$1,368	$1,939	-$17,948	$3,222	$3,942	-$4,759
Cumulated Annual Net income		$19,425	$19,277	$19,627	$20,466	$21,835	$23,774	$5,826	$9,048	$12,990	$8,231
CASHFLOW STATEMENT											
Operational Cashflow		$22,005	$2,433	$2,931	$3,420	$3,949	$4,520	-$15,368	$5,803	$6,522	-$2,178
Cumulated Cashflow		**$22,005**	**$24,438**	**$27,369**	**$30,789**	**$34,738**	**$39,258**	**$23,891**	**$29,694**	**$36,216**	**$34,038**
Free Cashflow	$0	$22,005	$2,433	$2,931	$3,420	$3,949	$4,520	-$15,368	$5,803	$6,522	-$2,178
Operating Profit Margin		58%	-1%	2%	5%	7%	10%	-59%	14%	16%	-12%

Figure 23: Example of the financial statement for the system with battery sizing considering 50% for the baseline + irrigation scenario for the first ten years of the lifetime of the project.

The income statement includes:

1. Total revenue stream = Total deposit amount + Annual income generated by the monthly payments considering the collection success rate (both calculated in chapter 10)
2. Total cost stream = Annual OPEX (calculated in chapter 9) + Component replacement cost for the respective years (calculated in chapter 7 and 8) + Annual CEM Management cost.

3. Earnings before interest, taxes, depreciation and amortization (EBITDA) = Total revenue stream – Total cost stream.
4. Earnings before interest and taxes (EBIT) = EBITDA – Depreciation (details of depreciation calculations can be found in Appendix 1).
5. Earnings before tax (EBT) = EBIT (in this study, it is considered that there are no interest expenses, thus EBT = EBIT).
6. Taxes = 30% of the EBT if it has a positive value. If EBT is negative, the tax should be zero.
7. Annual net income = EBT – Taxes (calculated in step 6).
8. Cumulated net income = Annual net income + Previous annual net income.

The cash flow includes:

1. Operational cash flow = Total revenue stream - Total cost stream – Taxes.
2. Cumulated cash flow = Operational cash flow + Previous operational cash flow.
3. Free cash flow = Operational cash flow.
4. Operating profit margin = EBT/Total Revenue Stream

The financial statements were designed considering a 100% grant donor model. A salary of $8,000 per year has been considered for CEM central business manager. The nominal discount rate and inflation rate considered are 10% and 8%, respectively. A collection success rate of 95 % has been considered [6].

For each scenario considered in the study, the financial statements described above were developed to determine the minimum necessary number of Energy Hubs installations needed to keep a positive cumulated cash flow over 20 years. A positive cumulated cash flow means that the model can sustain the on-going operational costs of the deployed installations and the central business manager.

The tool also calculates the total grant required to deploy the determined minimum necessary number of Energy Hubs installations needed to keep a positive cumulated cash flow, the net present value (NPV) of the free cashflow and consequently, the percentage of CAPEX recovered. The determination of the percentage of CAPEX recovered is relevant as it can judge subsidy requirements after evaluation of results.

A summary of the outputs from the financial statements for the four different scenarios considering the different DoD is shown in the next sections. The details of the financial statements for each scenario can be found in Appendix 1.

11.1 Baseline scenario

A summary of the most relevant outputs from the financial statements for the baseline scenario is presented in Table 41.

Table 41: Summary of relevant outputs from the financial statements for the baseline scenario.

Outputs			
Summary	**System with Battery - 80% DoD**	**System with Battery - 50% DoD**	**System with Battery - 30% DoD**
Minimum number of systems	19	14	12
Total grant	$ 432,744.00	$ 339,024.00	$ 325,152.00
Final cumulated cashflow	$ 215,412.03	$ 142,128.90	$ 111,064.26
% CAPEX recovered	50%	42%	34%

11.2 Baseline + Irrigation scenario

A summary of the most relevant outputs from the financial statements for the baseline + irrigation scenario is presented in Table 42.

Table 42: Summary of relevant outputs from the financial statements for the baseline + irrigation scenario.

Outputs			
Summary	**System with Battery - 80% DoD**	**System with Battery - 50% DoD**	**System with Battery - 30% DoD**
Minimum number of systems	5	5	4
Total grant	$ 269,471.00	$ 276,671.00	$ 232,856.80
Final cumulated cashflow	$ 131,221.66	$ 148,289.83	$ 73,824.24
% CAPEX recovered	49%	54%	32%

11.3 Baseline + Mill scenario

A summary of the most relevant outputs from the financial statements for the baseline + mill scenario is presented in Table 43.

Table 43: Summary of relevant outputs from the financial statements for the baseline + mill scenario.

Outputs

Summary	System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Minimum number of systems	7	5	4
Total grant	$ 414,526.42	$ 317,690.30	$ 294,472.24
Final cumulated cashflow	$ 305,555.10	$ 208,719.44	$ 148,254.55
% CAPEX recovered	74%	66%	50%

11.4 Baseline + Irrigation + Mill scenario

A summary of the most relevant outputs from the financial statements for the baseline + irrigation + mill scenario is presented in Table 44.

Table 44: Summary of relevant outputs from the financial statements for the baseline + irrigation + mill scenario.

Outputs

Summary	System with Battery - 80% DoD	System with Battery - 50% DoD	System with Battery - 30% DoD
Minimum number of systems	3	3	2
Total grant	$ 269,631.03	$ 282,591.03	$ 208,554.02
Final cumulated cashflow	$ 136,592.79	$ 170,886.56	$ 39,859.82
% CAPEX recovered	51%	60%	19%

12 Engagement and practical consultation with CEM

The results produced by the Energy Hub tool are based in the literature review and other previous studies developed in rural villages in Malawi. Although results were generated from relevant examples, real data is necessary to populate the tool and then, generate more accurate results allowing a better evaluation of the viability of the project and mitigation of risks while deploying the systems.

12.1 Survey

A survey based on structured questionnaires to gather quantitative and qualitative data related to the PUE types that have been considered in the Energy Hub tool was developed in partnership with CEM to generate input data for the tool and enable wider application in future projects.

A crucial part of this endeavour is to go beyond the assessment of the need of some business in the selected villages where the survey will be conducted, and begin to establish a baseline of representative data for the real demand for services or products offered by those businesses, as well as the ability to pay for the services or products. To this end, the survey was structured around three broad topics:

- Small services and sales business including phone charging, groceries, barber shop and video show;
- Irrigation farming including crop information, harvest time and land size of members of the community;
- Maize milling including distribution of the maize production along the year and defined quantity to be processed.

The survey is a valuable way to generate insights to understand the business environment in the villages and select the most appropriate PUE types to be included in the Energy Hub according to the frequency of use of products and services and how much money is spent already on these products and service. Surveys started to be conducted by CEM researchers in Dedza area during field work between August and September 2019.

The CEM researchers are responsible for the quality control of the survey collection data from a targeted group of people in the selected villages, including consistency and completeness inspections, as well as reporting fieldwork observations, problems and challenges while conducting the survey back to the UoS E4D team.

A digital platform called Kobo Toolbox was utilised to assist in the design of questionnaires and conduction of surveys. Kobo Toolbox is a free open-source suite of tools for mobile field data collection for use in challenging environments developed in partnership with researchers at the Harvard Humanitarian Initiative [41]. The data gathered will be analysed in Microsoft Excel and serve as new input data for the Energy Hub tool to assist in system design and business planning. An outline of the questionnaires can be found in Appendix 1.

13 Sensitivity Analysis

Sensitivity analysis allows exploration around uncertain parameters to test the robustness of outputs generated by the original model. In this study, sensitivity analysis is performed for five different parameters, which are the percentage of the deposit, number of monthly payments, nominal discount rate, inflation rate and the collection success rate. The two first parameters are related to the funding structure while the others are related to the financial statements.

13.1 Deposit

In the original model, the deposit rate is set to 10% of the total loan amount issued to an entrepreneur. To evaluate the influence of the deposit rate in the final percentage of CAPEX recovered over 20 years, the values of 5%, 7.5%, 12.5% and 15% have been considered for the analysis.

For 5% and 7.5% deposit rate, all scenarios show a shift by +5% and +10% of CAPEX recovered, respectively. For 12.5% and 15% deposit rate, all scenarios show a shift by -%5 and -10% of CAPEX recovered, respectively. Therefore, observing the effect of the deposit rate sensitivity, it can be seen that higher deposit rates, reduce the final percentage of CAPEX recovered and the opposite occurs for lower deposit rates, which increase the final percentage of CAPEX recovered. Figure 24 shows the effect of changes in the deposit rate to the CAPEX recovered for the baseline scenario (battery sizing 80% DoD).

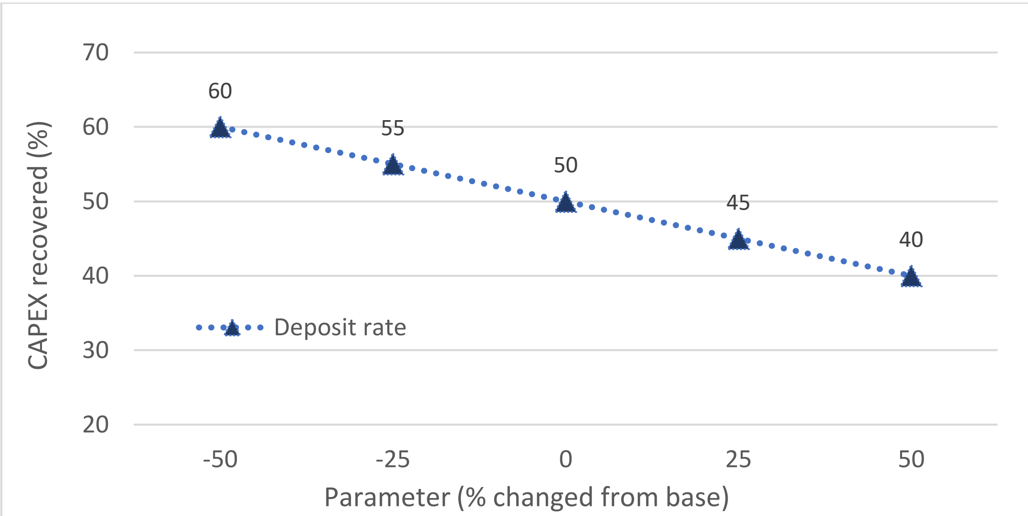

Figure 24: Sensitivity of CAPEX recovered considering deposit rate as parameter.

13.2 Number of monthly payments

In the original model, the number of monthly payments is set to 240 considering a 20 years project lifetime. To evaluate the influence of the number of monthly payments in the final percentage of CAPEX recovered over 20 years, the values of 180 (15 years) and 120 (10 years) have been considered for the analysis.

For 180 monthly payments, all scenarios show a shift between -39% and -41% of CAPEX recovered. In this case, the only scenario that still have part of CAPEX recovered for all battery sizing with different DoD considered is the baseline + mill. All the other scenarios show a negative CAPEX recovered, which means that the funding model is not able to appropriately recover the costs to sustain the on-going expenses of the system. For 120 monthly payments, all scenarios show a negative CAPEX recovered with the systems only being able to fully recover the costs to sustain the on-going expenses of the system during the first 14 years of operation.

13.3 Nominal discount rate and inflation rate

In the original model, the nominal discount rate is set to 10% and inflation rate is set to 8%. To evaluate the influence of the nominal discount rate in the final NPV, the values of 5%, 7.5%, 12.5% and 15% have been considered for the analysis. To evaluate the influence of the inflation rate in the final NPV, the values of 4%, 6%, 10% and 12% have been considered for the analysis.

For all nominal discount rates considered lower than 10%, all scenarios show an increase of the final NPV of the project. For all nominal discount rates considered higher than 10%, all scenarios show a reduction of the final NPV of the project. Therefore, observing the effect of nominal discount rates sensitivity, it can be seen that the plotted results of final NPV have the behaviour of an exponential curve with decreasing results when the nominal discount rate increases.

For all inflation rates considered lower than 8%, all scenarios show a reduction of the final NPV of the project. For all inflation rates considered higher than 8%, all scenarios show an increase of the final NPV. Therefore, observing the effect of inflation rates sensitivity, it can be seen that it has a reverse trend compared to nominal discount rates. The plotted results have a behaviour of an exponential curve with increasing results when the inflation rate increases.

Figure 25 shows the effect of changes in the nominal discount rate and inflation rate to the final NPV for the baseline + irrigation scenario (battery sizing 50% DoD).

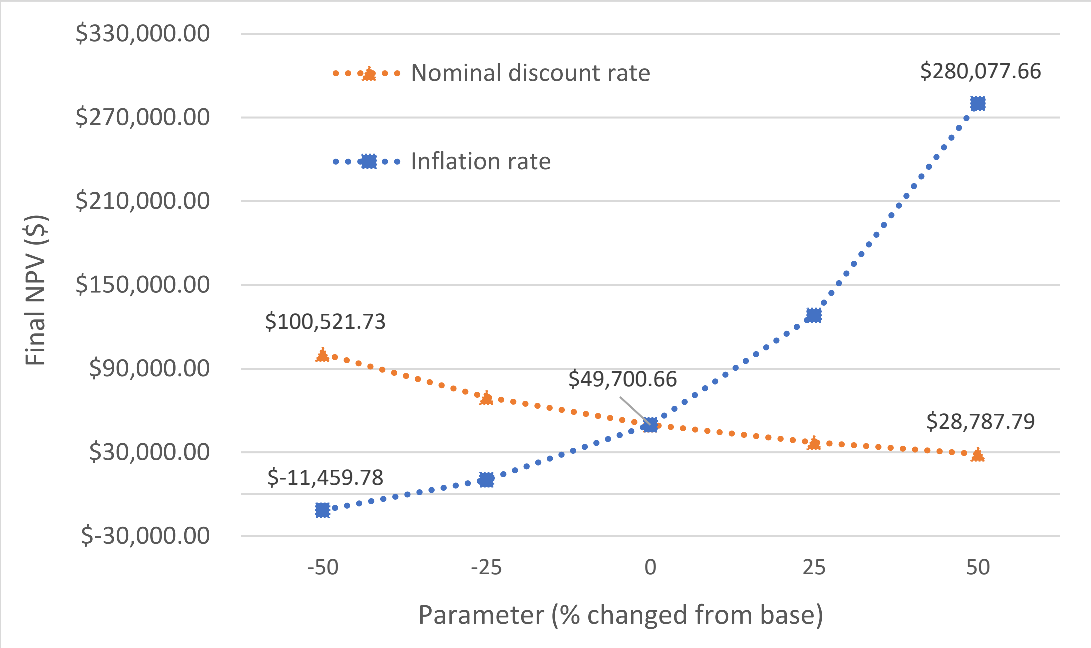

Figure 25: Sensitivity of final NPV for the baseline + irrigation scenario (battery sizing 50% DoD) considering nominal discount rate and inflation rate as parameters.

13.5 Collection success rate

In the original model, the collection success rate is set to 95%. To evaluate the influence of the collection success rate in the cumulated cash flow along the project lifetime, which is 20 years, the values of 100%, 90% and 85% have been considered for the analysis. The collection success rate is a crucial parameter to be analysed as it can check the sustainability of the system assuming that the entrepreneurs can face some challenges and not be able to meet their payment obligations.

For a collection success rate of 100%, all scenarios present improved positive cumulated cash flows as expected. This change affected mostly the systems considering battery sizing with 80% DoD as it was possible to have a higher cumulated cash flow after 10 years of operation when it is necessary to replace the inverter and battery bank at the same time. Figure 26 shows the comparison of the cumulated cash flow for the baseline scenario with battery sizing with 80% DoD considering collection success rate of 95% and 100%.

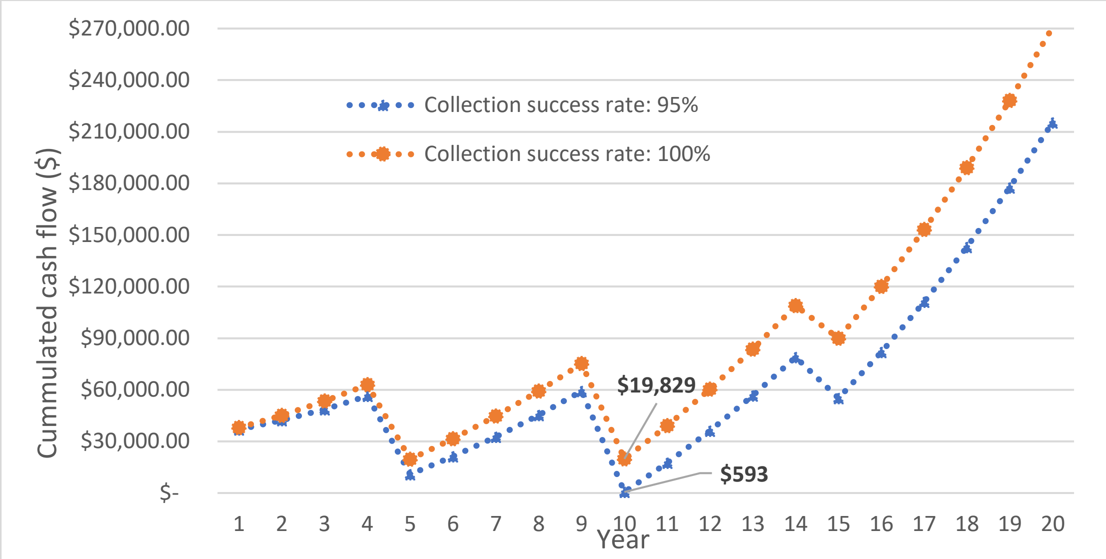

Figure 26: Comparison of the cumulated cash flow for the baseline scenario with battery sizing with 80% DoD considering collection success rate of 95% and 100%.

For a collection success rate of 90%, each scenario present different results for the cumulated cash flow. In the baseline scenario, all systems considered (battery sizing with 80%, 50% and 30% DoD) show a negative cumulated cash flow after 7 years of operation, which means that the funding model is not able to appropriately recover the costs to sustain the on-going expenses of the system. Figure 27 shows the sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline scenario including battery sizing with 80%, 50% and 30% DoD. The 'sustainability limit' line determines a negative cumulated cash flow for any year.

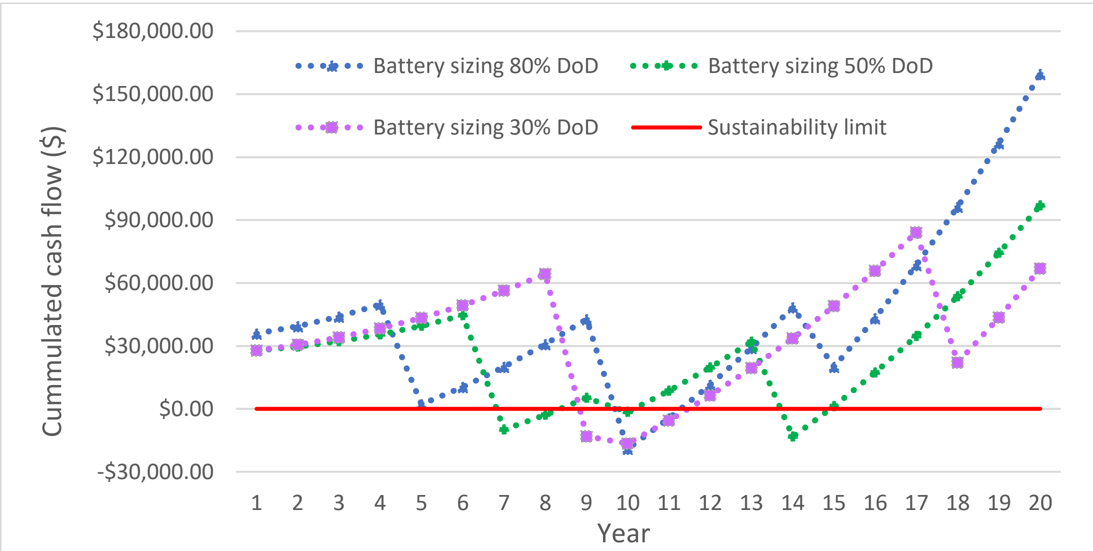

Figure 27: Sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline scenario.

In the baseline + irrigation scenario, the only system that show a positive cumulated cashflow during the 20 years is the system considering battery sizing with 80% DoD. The other systems show a negative cumulated cash flow after 10 years of operation. Figure 28 shows the sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline + irrigation scenario including battery sizing with 80%, 50% and 30% DoD.

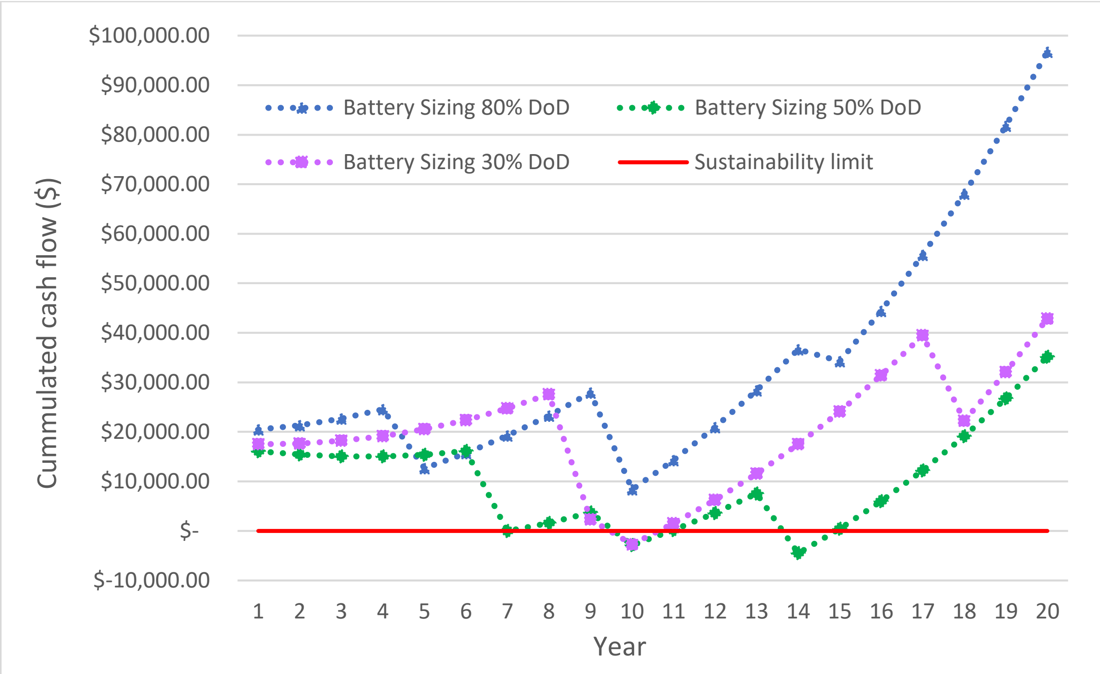

Figure 28: Sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline + irrigation scenario.

For both baseline + mill scenario and baseline + irrigation + mill scenario, the only system that show a positive cumulated cashflow during the 20 years is the system considering battery sizing with 50% DoD. The other systems show a negative cumulated cash flow after 9 years of operation for both scenarios, which means that the funding model is not able to appropriately recover the costs to sustain the on-going expenses of these systems. Figure 29 and Figure 30 show the sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline + mill scenario and baseline + irrigation + mill scenarios, respectively, including battery sizing with 80%, 50% and 30% DoD. It can be seen that the baseline + mill scenario present results closer to the sustainability limit in years 9 and 10. In the other hand, the baseline + irrigation + mill scenario present results far from the sustainability limit between the years 9 and 12.

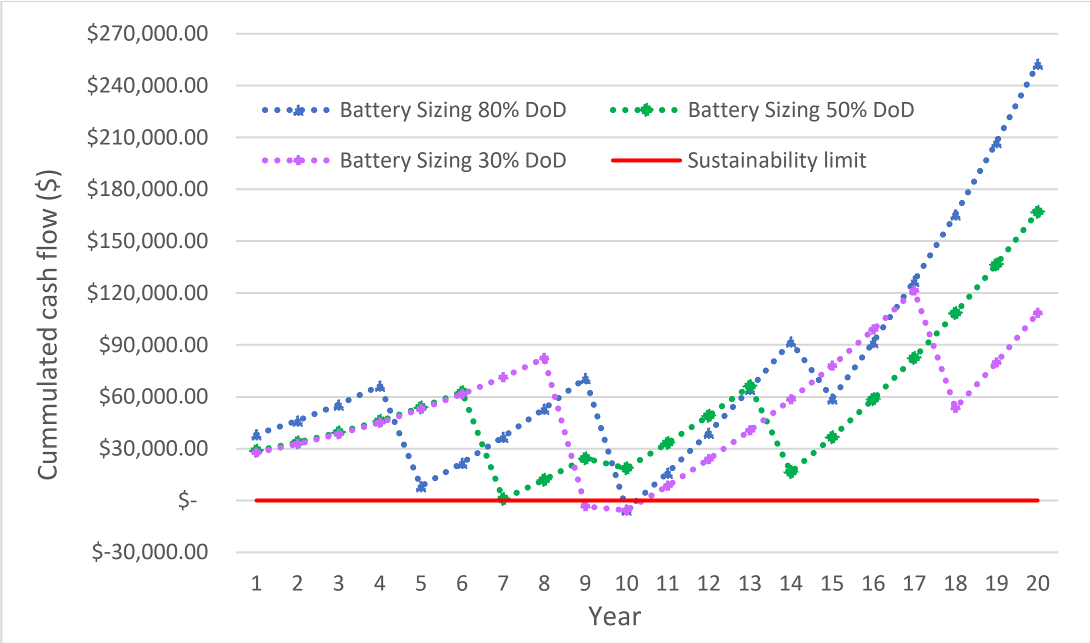

Figure 29: Sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline + mill scenario.

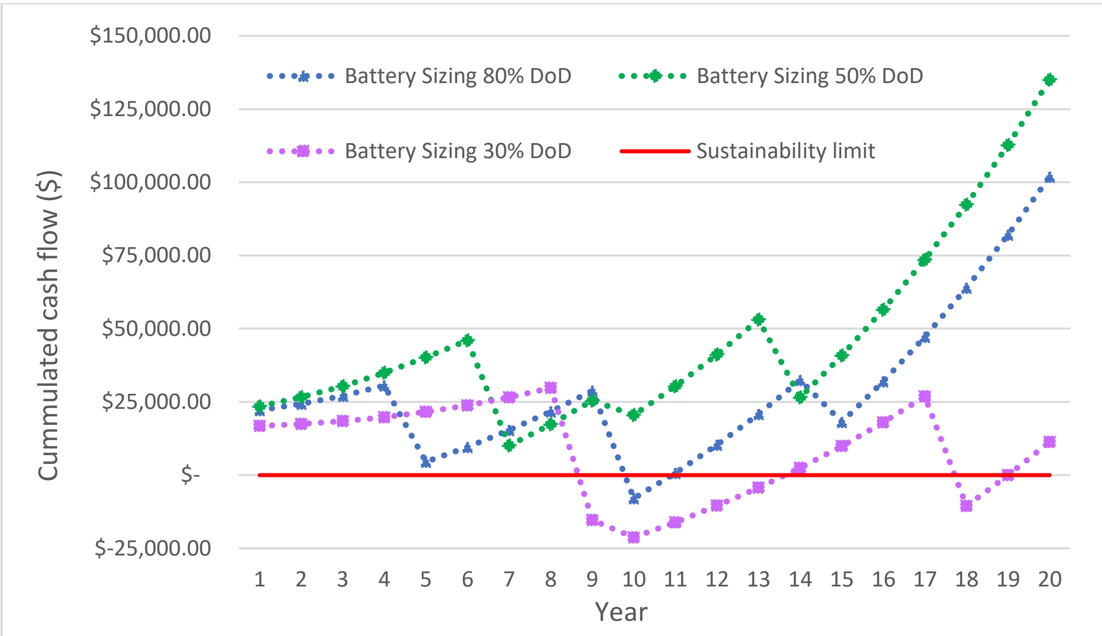

Figure 30: Sensitivity of cumulated cash flow considering collection success rate of 90% for the baseline + irrigation + mill scenario.

Finally, for a collection success rate of 85%, the only system that shows a positive cumulated cashflow during the 20 years is the system modelled for the baseline + irrigation + mill scenario considering battery sizing with 50% DoD. Thus, it can be considered the most robust system within the scenarios modelled.

14 Results

An overview of the main results generated by the Energy Hub tool is presented in the next sections. The results are divided in two categories: findings for each scenario that identify the optimum battery DoD configuration for the Energy Hub installation and findings within the scenarios that identify the optimum Energy Hub configuration according to the scenarios considered.

The results presented include the minimum necessary number of Energy Hubs installations needed to keep a positive cumulated cash flow, the total grant required, and the percentage of CAPEX recovered over 20 years. The optimal configuration is the one that have the best balance of keeping the cumulated cash flow positive, minimising upfront grant and accumulating cash in the bank over the system lifetime (capital recovery).

14.1 Identification of the most favourable battery DoD configuration for the Energy Hub installation

The system modelled that presented the most favourable financial results for all scenarios considered is the system with battery sizing considering 50% DoD. It presented an optimized result for the final CAPEX recovered considering the initial total grant required to deploy the minimum number of installations needed to sustain the system. Table 45 shows the summary of financial outputs for the systems with battery sizing considering 50% DoD of each scenario.

Table 45: Summary of financial outputs for the systems with battery sizing considering 50% DoD of each scenario.

Summary	**Baseline Scenario**	**Baseline + Irrigation scenario**	**Baseline + Mill scenario**	**Baseline + Irrigation + Mill scenario**
Systems to deploy	14	5	5	3
Total grant required	$ 339,024.00	$ 276,671.00	$ 317,690.30	$ 282,591.03
Cumulated cashflow	$ 142,128.90	$ 148,289.83	$ 208,719.44	$ 170,886.56
% CAPEX recovered	42%	54%	66%	60%

The systems modelled with battery sizing considering 30% DoD presented the smaller minimum number of necessary installations to be deployed to sustain the on-going operational costs of the system and consequently, the minimum total grant required. Despite the optimized results for the upfront grant required, the CAPEX recovered was reduced considerably reaching a maximum of 50% for the system modelled in the baseline + irrigation scenario. Table 46 shows the summary of financial outputs for the systems modelled with battery sizing considering 30% DoD of each scenario.

Table 46: Summary of financial outputs for the systems with battery sizing considering 30% DoD of each scenario.

Summary	Baseline Scenario	Baseline + Irrigation scenario	Baseline + Mill scenario	Baseline + Irrigation + Mill scenario
Systems to deploy	12	4	4	2
Total grant	$ 325,152.00	$ 232,856.80	$ 294,472.24	$ 208,554.02
Cumulated cashflow	$ 111,064.26	$ 73,824.24	$ 148,254.55	$ 39,859.82
% CAPEX recovered	34%	32%	50%	19%

14.2 Identification of the most favourable Energy Hub configuration

Each scenario proposed in the study presents a specific configuration with a combination of different PUE types. As it can be seen in the Table 45 in section 14.1, the CAPEX recovered in the end of the lifetime of the project increases depending on the different PUE types included in the Energy Hub.

Considering Table 45, the systems that presented the most favourable financial results are the systems modelled in the baseline + mill scenario and baseline + irrigation + mill scenario, with a CAPEX recovery of 66% and 60%, respectively.

Despite the higher CAPEX recovery of these systems, they presented the highest monthly fee calculated in chapter 10 for the entrepreneur having a maize mill business, which according to previous studies seems not in line with the ability to pay of members of rural communities in Malawi [6]. In addition, the sensitivity analysis performed in chapter 13 shows the system modelled in the baseline + mill scenario is highly sensitive for changes in the collection success rate, which indicates a risk for the viability of the project. Therefore, the high priority, or most viable Energy Hub configuration has been shown to be the system modelled in the baseline + irrigation scenario as it also presents a reasonable CAPEX recovery of 54% when deploying minimum of five installations and shows lower sensitivity for changes in the collection success rate compared to the system modelled in the baseline scenario.

14.3 Survey data collection

The survey data collection has been conducted in villages in Dedza area in Malawi. Data results of the survey need to be analysed and transformed in real input data to populate the Energy Hub tool which will generate representative results for monthly payments considering the ability to pay of members of rural communities in Malawi.

15 Discussion and Recommendations

The aim of this study is to evaluate the viability of the deployment of Energy Hubs in rural communities in Malawi identifying the optimal Energy Hub configuration and battery's DoD as well as how many Energy Hubs installations need to be deployed to keep the cumulated cash flow positive, as well as evaluating what are the implications for upfront grants.

The optimal Energy Hub configuration considering the battery's DoD has been identified as the Energy Hub modelled in the baseline + irrigation scenarios with a battery DoD of 50%. This configuration presented the best balance of keeping the cumulated cash flow positive, minimising upfront grant and accumulating a reasonable amount of cash in the bank over the system lifetime (capital recovery). In addition, this configuration does not carry the uncertainties regarding the calculated monthly fee for the maize mill business and shows lower sensitivity for changes in the collection success rate compared to the system modelled in the baseline scenario.

15.1 Discussion of results

The overall outcomes demonstrate that whilst an Energy Hub delivery model can operate successfully, none of the systems could recover 100% of the initial CAPEX when deploying the minimum necessary number of installations required to sustain the on-going costs of the system. For the scenarios considered in this analysis, the systems modelled presented a CAPEX recovery between 19% and 74%. The optimal Energy Hub configuration presented a CAPEX recovery of 54% with a minimum of 5 installations required as presented in Table 45. For this reason, the Energy Hub delivery model require a subsidy to be viable. The subsidy will encourage the deployment of off-grid PV systems for PUE while providing financial support to cover the part of the CAPEX that is not recovered by the own system.

15.1.1 Changes in the number of installations required

The Energy Hub tool calculates the minimum number of installations required to keep a positive cumulated cash flow that sustain the on-going costs of the system. If a lower number of installations is deployed than the determined in chapter 14, a negative cash flow will be identified in some years, mostly in the years determined for replacement of components. In this case the initial total grant needed would be reduced, however some facility to finance the negative cumulated cash flow would be needed over the project lifetime to guarantee the sustainability of the system and make possible a breakeven after 20 years.

The impact of reducing the number of installations on the cumulated cash flow varies considerably within the systems modelled. For the system considering battery sizing with 50% DoD modelled in the baseline scenario, the deployment of thirteen installations (one installation less than the determined – see Table 45), presents a negative cash flow only in the 7th year of operation. However, the impact is much more relevant for the system considering battery sizing with 50% DoD modelled in the baseline + irrigation + mill scenario that presents a negative cash flow in the 7th year of operation until the rest of the project lifetime when deploying two installations (one installation less than the determined – see Table 45).

If a higher number of installations is deployed than the determined in chapter 14, an improved positive cash flow will be identified, mostly in the years determined for replacement of components. In this case the initial total grant needed would be increased and a 100% CAPEX recovery becomes possible. Similarly to the previous change, the impact varies considerably within the systems modelled. Table 47 presents the minimum number of necessary installation and the total grant necessary for a 100% CAPEX recovery for all scenarios considering a battery sizing with 50% DoD.

Table 47: Minimum number of necessary installation and the total grant necessary for a 100% CAPEX recovery for all scenarios considering a battery sizing with 50% DoD.

Outputs - Battery Sizing with 50% DoD

Summary	Baseline	Baseline + Irrigation	Baseline + Mill	Baseline + Irrigation + Mill
Installations	90	10	10	12
Total grant	$ 2,203,656.00	$ 553,342.00	$ 635,380.60	$ 1,130,364.12
% CAPEX recovered	100%	100%	100%	100%

According to Table 47, the system modelled in the baseline + irrigation scenario presents a CAPEX recovery of 100% with the smallest total grant required when deploying a minimum of ten installations compare to the other scenarios considered.

15.1.2 System sustainability

It has been revealed that the scenarios considered in the Energy tool have different ability to accumulate cash (capital recovery) over the lifetime of the project. Considering that the Energy Hub will be delivered under the CEM model (a social enterprise) the percentage of CAPEX recovered would be reinvested into other energy access initiatives.

Finally, when placing the Energy Hub within a rural area, it is important to consider the social implications as the area will be sensitive to change. In addition, the entrepreneurs involved in the Energy Hub require special training such as basic bookkeeping, accounting, and business planning.

15.2 Recommendations

The deployment of off-grid system for productive use has developed very quickly in many SSA countries, resulting in many opportunities to improve the effectiveness of energy provision for PUE types. As a result of the main outcomes from this study, the following recommendations can be made:

- The inclusion of more PUE types in the Energy Hub configuration can effectively increase the final CAPEX recovered, even when accounting for infrastructure and equipment cost. However, it is crucial to understand the size of load, time of use, and seasonality— the match of different PUE types within the Energy Hub optimizes the energy delivered by the PV system.
- The inclusion of PUE types with flexible loads, such as water pumps, maximizes the generation capacity utilization and increase the final CAPEX recovered. Flexible loads can reduce or even exclude the need of the battery bank. As a result, component replacement costs during the lifetime of the project are reduced considerably.
- Battery sizing considering 50% DoD should be preferable for the system design of the Energy Hub delivery model as it allows a higher positive cumulated cashflow before the first replacement of the batteries, even when accounting for the extra cost to have a bigger battery bank.

- The initial deployment of Energy Hubs should first focus on one specific region first aiming to identify potential local entrepreneurs that can join the Energy Hub model. By concentrating projects in one specific geographic area, the transportation and servicing costs to maintain the system are reduced.
- Pilot projects of Energy Hub should be implemented, specifically for the PUE types included in the baseline + irrigation scenario. The implementation of a pilot project will provide representative data collection and effective monitoring of load profiles.

15.3 Limitations

As mentioned previously, the methodology taken in this study has allowed for reasonable estimates to be deduced with regards to the viability of deployment of Energy Hubs in rural communities in Malawi. However, there were several limitations to this study which will have prevented results of a higher accuracy.

Given more time, real data on demand for PUE types, willingness and ability to pay by businesses and the exact size of the irrigation scheme/maize mill needed could have been analysed in greater detail through data that has been gathered by the survey developed in partnership with CEM. An attempt to mitigate this was to use data from previous studies conducted in rural communities in Malawi and other countries in SSA, which provided a stronger basis for calculations. However, some reasonable estimations still had to be made in place of real data.

In addition, accurate load profile growth patterns were difficult to find and vary depending on community characteristics. Some load growth has been included into the system design in the inverters and cables sizing, however further modelling of load growth is necessary to determine when PV modules and batteries need to be added to the system to keep its reliability.

The viability of the Energy Hub delivery model has been analysed considering a 100% grant donor model. Future research is necessary to evaluate the viability of Energy Hubs considering debt financing or other sources of external funding.

Finally, it was assumed in this study when calculating the final CAPEX recovered that components depreciated 100% in the end of the project lifetime, so no salvage is considered. This may not be the case, mostly for systems with battery sizing considering DoD of 50% and 30%. Therefore, further research into this topic is needed as it could have improved the accuracy of the final CAPEX recovered.

15.4 Further work

The Energy Hub tool created, and the survey developed to gather representative data to populate the Energy Hub tool can be used in future studies to determine the applicability and viability of Energy Hubs in rural communities in Malawi and other countries in SSA. During the course of this work, several further areas of study which could provide useful insights for a better investigation of the viability of deployment of Energy Hubs were highlighted.

The data gathered by the survey that has been conducted in rural villages in Dedza area has not been yet available to generate more representative input data in order to populate the Energy Hub tool. In order to precisely investigate the viability of Energy Hubs in Malawi, a continuous flow of information into the Energy Hub tool is necessary. The information gather by the survey will allow a more appropriate selection of PUE types as the demand for products and services will be analysed. In addition, the results generated for the monthly fee can be verified as the willingness and ability to pay of members of the community will be assessed.

The literature review identified many barriers while deploying off-grid PV system for productive use in rural communities in SSA. Many of the barriers are related to the economic viability of the off-grid system in long term. Thus, there is a potential for the Energy Hub tool created in this study to be developed further. Some examples would be to add more PUE types and scenarios, evaluate load profiles in greater depth and consider different funding models. To evaluate the viability of the project in different environments. This would provide a highly useful tool for evaluation of PUE for rural development.

It was acknowledged that off-grid PV systems that use AC appliances as part of their systems design have higher CAPEX. The higher CAPEX is due to the higher overall energy consumption of AC appliances that are not designed for off-grid environment and the need for an inverter. In order to precisely investigate the viability of Energy Hubs in Malawi it is required to consider DC appliances as a design option. Benefits from use of DC systems may lead to a significant reduction in overall energy consumption and costs in comparison to AC system. As a result, overall generation and storage capacity requirements can be minimised, reducing overall costs of the system. Although DC appliances can introduce significant energy saving (in comparison to AC appliances) problems arise with its supply chain. Currently market is dominated by AC appliances and use of DC appliances may be very challenging.

Finally, the scope of this study did not consider the evaluation of social and environmental impact analysis. The introduction of a system providing electricity for productive use within a small rural community in SSA can have significant social and environmental implications, therefore an in-depth social and environmental impact analysis on the deployment of Energy Hubs would be highly beneficial to the implementation of such schemes.

15 Conclusion

This study aimed to evaluate the viability of the deployment of Energy Hubs in rural communities in Malawi identifying the optimal Energy Hub configuration and battery's DoD and determining as how many Energy Hubs installations need to be deployed to keep cash flow positive, as well as evaluating what are the implications for upfront grants.

An overview of relevant literature was carried out to understand the challenges while deploying off-grid system in rural communities. An Energy Hub tool was developed to allow the assessment of the viability of different Energy Hub configurations based on the ability of the system to keep a positive cash flow while minimising the upfront grant and maximising the cash in the bank over the system life time (capital recovery). Practical consultation with CEM was then carried out for the development of a survey based on structured questionnaires to generate input data for the tool and enable wider application in future projects. Lastly, a sensitivity analysis was performed to evaluate the robustness of the results generated by the Energy Hub tool.

The optimal Energy Hub configuration considering the battery's DoD has been identified as the Energy Hub modelled in the baseline + irrigation scenarios with a battery DoD of 50%. This configuration presented a positive cumulated cash flow during the whole lifetime of the project when deploying a minimum number of five installations. The required initial total grant required is $276,671.00 and it is capable of recovering 54% of the initial CAPEX.

Based on the results, the scenarios considered in the Energy tool have different ability to accumulate cash (capital recovery) over the lifetime of the project. Considering that the Energy Hub will be delivered under the CEM model (a social enterprise) the percentage of CAPEX recovered would be reinvested into other energy access initiatives. Therefore, although the Energy Hub model is not financeable from standard loans, upfront grants can enable not just Energy Hubs projects, but wider impact in rural communities.

Further research into the willingness and ability to pay of members of the community must be investigated to validate results generated by the Energy Hub tool. Additionally, Energy Hubs configurations considering DC appliances should be investigated as it may lead to a significant reduction in overall generation and storage capacity requirements minimising overall costs of the system.

Finally, the Energy Hub tool developed in this study can be accessed for use and applied in any location to evaluate the technical and financial viability of the deployment of Energy Hubs in rural communities.

Appendices

Appendix 1

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