Assessing the Feasibility of a Solar Microgrid Social Enterprise in Sub-Saharan Africa

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Abstract

Delivering Sustainable Development Goal 7 by providing secure, affordable and reliable access to modern electricity for over 700 million people globally demands innovation in technology, policy and delivery models. Solar PV microgrids, defined as energy generation and supply systems having capabilities of managing local energy supply, are proving a viable solution for remote rural areas in Sub-Saharan Africa with no prospect of main grid connection. While steady technological progress in the microgrid sector is being observed, effective planning methodologies and delivery models are key to sustainable microgrid implementation. Social enterprise is a collective term for a range of organisations that trade for a social purpose, and offer a niche innovative energy access delivery model that is neither public nor private sector, achieving primary social goals through active marketplace trade. This thesis proposes an evidence-based analysis methodology for assessing the feasibility of deploying and operating solar microgrids as a social enterprise in a low-income developing country through assessing financial sustainability and social impact. The former is assessed through conducting a site-specific feasibility study; assessing the market potential over a given region; and business scale-up scenario modelling, while the latter is assessed through a novel key performance indicator framework. The methodology is tested on a use case in Malawi, where pilot microgrids provide primary data to inform SMSE feasibility. Results indicate a SMSE operating a 10 site portfolio offer a positive IRR and investment opportunity, with interventions on reduced CAPEX and OPEX and 50% grant contributions. Positive social impact is experienced by the community served by the microgrid in economic development, health, and education. The methodology is validated through the use case testing with recommendations provided for improved functionality. Further recommendations are given for interventions in the Malawian energy eco-system to remove barriers for improved SMSE feasibility, directed at policy makers, microgrid developers and research agendas.

Key words: SDG7, Energy Planning, Delivery Models, Solar Microgrids, Social Enterprise

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1 Research introduction and justification

1.1 Overview and justification of developing and testing a methodology to determine the feasibility of solar microgrid social enterprises

Energy is the golden thread that connects economic growth, social equity and environmental sustainability [1]. While in the last decade, the global electrification rate has risen from 83% to 89%, 770 million people are still without access to electricity [2] and it is estimated that at current rates a projected 650 million people will remain without access to electricity in 2030, with 9 out of 10 of these from Sub-Saharan Africa (SSA). This challenge is highlighted by the United Nations Sustainable Development Goal 7: Access to Clean, Reliable, and Affordable Energy and being addressed by the United Nations Sustainable Energy for All initiative [3], but the problem inherently demands new and innovative solutions for rural electrification. This problem is particularly acute in Malawi, where just 18% of the population have access to electricity with grid electricity contributing 11.4% while off grid solar PV accounting for the remaining 6.6% [4]

Energy poverty constrains economic growth, handicaps the development of self-sufficient local communities, and threatens security [5]. Pathways for electrification include national grid expansion solutions to interconnect urban or rural areas through centralised electrical grids; and off-grid solutions such as solar lighting systems, solar home systems, and micro/mini-grids [6]. Grid expansion solutions have been successfully employed in urban locations with dense population, high-energy consumption, and economic activity allowing for extensive use of income-generating equipment. Such solutions can be the costliest in terms of capital investment but traditionally the most reliable and with the lowest lifetime energy cost [7]. However, remote and rural communities consume significantly less energy per capita than urban populations, making grid expansion cost prohibitive and increasing the challenges of connecting these last mile communities [8]. An urban-rural divide has arisen, especially in Sub-Saharan Africa, where only 31.5% the rural population have access to electricity compared to 78.1% of urban populations [4]. Energy poverty is one of the driving forces behind urban migration with African cities growing much faster than other cities around the world [10] [9]and the influx into poor, urban neighbourhoods without necessary infrastructure creates inadequate living conditions and destabilizes communities.

Off-grid solutions can provide a pathway to rural electrification with mini-grids being the most economically viable option for servicing areas that are too expensive for the main grid to reach in a timely manner but have high enough demand and population density to support commercial viability [10]. It is estimated that to achieve the 2030 electrification goal for the remaining rural locations, at least 210,000 new mini grids need to be employed serving 490 million people and requiring a total investment of more than $220 billion[11].

Mini-grids, microgrids and nanogrids, defined as a set of electricity generators and energy storage systems interconnected to a distribution network supplying electricity to a localised group of customers [12], are proving to be a viable solution for rural (and peri-urban) areas unlikely to receive grid connection in the near future. The microgrid market is on the rise globally, due in part to decreasing costs of renewable energy technologies, specifically solar PV modules and battery storage [13]. Increasing numbers of solar microgrid installations are being observed in East Africa with companies such as PowerGen [14] MeshPower [15] and SteamaCo [16] advancing innovation in technology for microgrid metering, monitoring and control as well as business models and tariff setting.

With the mentioned cost reductions in solar PV components coupled with high solar resource, there has been increasing interest in implementing solar PV microgrids in Malawi, especially in areas unlikely to receive a main grid connection in the near future [17]. Given the high percentage of population currently unserved by the national grid, the potential market for solar microgrids is large. The scale of microgrids addresses a gap in the market, fulfilling a niche that offers higher levels of access than Solar Home Systems (SHS) or Pico Solar Products (PSP), but faster to implement and with lower capital costs than larger mini-grid systems [18].

Accelerating solar microgrid deployment demands more than technical research: effective energy planning methodologies are needed for sustainable microgrid implementation with sustainable business models that are financially sustainable yet fulfil the social development needs of the rural communities they serve. The concept of the ‘energy delivery model’ describes a core set of activities and actors that constitute the energy service, highlighting the importance of understanding end-users’ needs, the energy and non-energy gaps preventing them being met, and the supporting services required to make the energy infrastructure sustainable [19]. This concept also stresses the importance of considering wider enabling-environment policies, additional supporting services and ‘softer’, socio-cultural factors when designing and delivering energy services for poor groups. Synonymous with the concept of delivery models is that of business models for renewable energy and microgrid deployment. Although the crucial role of business, and of business-based approaches in development is increasingly emphasised by academics and practitioners, insight is lacking in analysis of viable business models, in environmental, social and economic terms [20].

Broadly defined as the use of market-based approaches to address social issues, social enterprise provides a “business” source of revenue for civil society organizations [21]. Seizing the opportunities presented by rapid changes in technology and the availability of renewable energy at continually falling costs, social enterprises have begun to fill in the gap between the public and private provision of electricity to address energy poverty [22]. Scholarly interest in social enterprise has progressed beyond the early focus on definitions and context to investigate their management and performance.

Solar microgrids can be operated as social enterprises therefore offering a promising and sustainable opportunity to contribute to the targets set by SDG7 [23]. However, the success of such organisations depends on their ability to address the energy trilemma: security, affordability, and sustainability, all of which must also incorporate social acceptance. Several projects have failed due to bad planning: high costs that surpass the community's ability to pay and leading to reduced connections; oversizing due to inaccurate load growth calculations; failure to incorporate the microgrid into the local economic ecosystem; inability to provide local support through the mini grid lifecycle; and failure to stimulate income-generating uses of electricity [24]–[26] [27]

To address these issues and ensure the success of future microgrid projects, it is essential to adopt a whole system socio-techno-economic approach for off-grid rural electrification project planning. High-quality integrated analysis tools utilising primary data can assist in such project planning, but many commercial planning tools focus on technical solutions and fail to incorporate the economic or social aspects of the problem. Other tools might provide some of these capabilities but at high prices often unattainable to the local workforce. Holistic planning tools and methodologies to inform decision-making and enable the successful design and implementation of solar microgrid social enterprises are required in order for them to scale in a sustainable manner.

The research contribution of this thesis addresses these challenges by taking a comprehensive, integrated and holistic approach to microgrid planning and business design by incorporating two emerging academic territories: social enterprises and solar microgrids. The research is applied in Malawi, where an identified need exists for innovative and sustainable rural electrification delivery models. It broadly considers the concept of utilising solar resource as an input to interlinked technical, economic and social microgrid systems to progress human development as part of a just transition. With few proven sustainable PV microgrid initiatives existing in developing countries, and none in Malawi, there is clear motivation for this useful and novel research.

1.2 Research questions, aims and objectives

The aim of this thesis is to set out and test an argument for Solar Microgrid Social Enterprises (SMSE) as a conduit for achieving Sustainable Development goal 7 (SDG7), with key objectives of proposing a methodology for assessing the feasibility of a SMSE, and testing it on a use case in Malawi. The research questions this thesis aims to address are as follows:

- Are solar microgrids, deployed and operated as a social enterprise a feasible solution to provide sustainable, reliable and affordable energy at scale in low-income countries?
- Can SMSEs be financially sustainable in balancing costs of capital, operation and maintenance with income from electricity sales?
- Do SMSEs offer measurable positive social impact on the communities they serve including poverty reduction and economic development?
- What actions and interventions are needed by developers and other stakeholders in the microgrid ecosystem to ensure sustainable operation and meaningful impact to be offered through solar microgrids at scale?

Chapter 2 locates this thesis within the existing industry and academic knowledgebase of solar microgrids and social enterprises. It comprises a literature review of definitions, global trends, advantages and limitations of solar microgrids, introduces the concept of a social enterprise, presents the existing knowledge base on measuring social impact of rural electrification, and maps the existing status quo of existing academic and industry literature on planning tools for mini-grid implementation. Chapter 3 then proposes an evidence based methodology to assess the feasibility of a SMSE. This is achieved through firstly assessing the financial sustainability of a SMSE by conducting a feasibility study for a defined use case, assessing the market potential over a given region and conducting business scale up modelling. Secondly, the methodology measures the social impact of SMSEs through piloting, monitoring and evaluation of SMESs through a novel key performance indicator framework, with recommendations provided for further utilising primary data from piloting to inform and refine the methodology. In Chapter 4, the proposed methodology is tested on a use case in Malawi, validating the methodology and drawing insight from a real life SMSE case study. Chapter 5 draws conclusions by presenting a robust discussion of both the feasibility assessment of an SMSE in Malawi, as well as the strengths, areas for improvement, accuracy, suitability and applicability of the proposed methodology, before suggestions for further research are outlined in Chapter 6.

1.3 Research contributions

This thesis has developed a methodology to conduct an evidence-based analysis of the feasibility of a social enterprise delivery model for the deployment and operation of solar microgrids in Sub-Saharan Africa, which involves assessing the financial sustainability and social impact. The methodology has then been tested using primary case study data in Malawi, offering insight to feasibility of a SMSE in Malawi and provides recommendations for scaling up the technology.

The research presented progresses the knowledgebase in academic and industry fields through combining established and novel methods, and presenting analysis of primary case study data. A concise positioning of the contribution this thesis makes within the academic and industry landscape of off-grid energy access and minigrid planning tools is outlined in Section 2.5, while a summary of gaps in incumbent literature which this thesis address are listed below,

- Although social enterprises are an emerging field of scholarly attention, few studies are focusing on renewable energy or solar microgrid applications of social enterprises. Literature suggests social enterprises are growing as a field of academic discourse, however little research has been conducted that systematically interrogates social enterprise practices or provides quantitative assessment of their business feasibility, especially when applied to microgrids.
- There is generally a lack of primary data from active mini and microgrid projects published in academic literature, and almost none in Malawi. This paucity of primary data limits the ability of government policy planners, microgrid developers and researchers to make informed decisions regarding microgrid technical design and business modelling.
- Although industry standard methods for tracking performance of mini and microgrids exist, most focus on technical and economic parameters with few offering insight to social impact offered to communities.
- Energy access planning tools exist, but few focus specifically on solar microgrids, and none that could be found that holistically allow feasibility assessment of solar microgrid deployment and operation at multiple scales utilising primary data.

In the field of energy access planning, specifically in relation to feasibility planning for solar microgrids operating as social enterprises, the thesis offers the following contributions:

- Literature based exploration of solar microgrids and social enterprises, proposing a set of defining characteristics of a ‘Solar Microgrid Social Enterprise’.
- Development of a methodology to assess the feasibility of SMSE, comprising assessing financial sustainability and tracking social impact.
- Development of a novel method for assessing the market potential for solar microgrids though linking techno-economic modelling to GIS mapping to compare microgrids with competitor technologies over a geographic region in least cost electrification pathway planning.
- Use of single site feasibility and market assessment outputs to model financial sustainability and investment case of a SMSE operating a portfolio of microgrids at scale, utilising new industry tool Odyssey.
- Development of a novel Key Performance Indicator framework to monitor performance and impact of solar microgrids, specifically designed to better understand the social impact offered by solar microgrids to the communities they serve.

The methodology has consequently been tested in Malawi, providing analysis of primary case study data from a nascent market with little to no previous published data. Specific contributions to the energy access and microgrid sector in Malawi are summarised below

- A quantification of the market for solar microgrids in Malawi in terms of population percentage served compared with competitor technologies, and estimated calculations for CAPEX and OPEX costs to fulfil this market share.
- Mapping of the Malawian microgrid ecosystem, revealing opportunities and barriers supporting or preventing microgrids from scaling in Malawi, with targeted recommendations provided to policy makers and microgrid developers to overcome the barriers.
- Utilisation of the KPI indicator framework in Malawi has revealed key insight on solar microgrid performance and impact in Malawi measured in technical, economic and social impact themes.
- Primary data on CAPEX and OPEX for a microgrid installed in Malawi, using 12 months of operating data.
- Demand data for previously unconnected microgrid customers, including load profiles for residential, business, and institutional customers.
- Indicators of Ability to Pay of rural Microgrid customers have been presented, through measured revenue collection from a pilot microgrid.
- An assessment of financial sustainability and investment case for a SMSE operating a portfolio of microgrids at scale in Malawi.
- An evidence base presented for use as advocacy toward subsidies for microgrids in Malawi.

In summary, the research presented here provides a contribution to the fields of energy access planning and solar microgrid business planning. It will be of utility to practitioners, researchers and policy makers in Malawi and other low-income Sub-Saharan countries through providing robust tools and data to inform minigrid deployment to help achieve SDG7.

1.4 Publications

1.4.1 Peer Reviewed Journal Publications

- Assessing the market for solar photovoltaic (PV) microgrids in Malawi | Eales, Aran; Alsop, Alfred; Frame, Damien; Strachan, Scott; Galloway, Stuart | Hapres Journal of Sustainability Research. Vol. 2, No. 1. (2020)
- Understanding Solar Microgrid Sustainability and Social Impact through a Novel Key Performance Indicator Framework | Aran Eales, Elizabeth Banda, Damien Frame, and Scott Strachan | Submitted to Elsevier Energy for Sustainable Development, January 2023

- Sustainability evaluation of community-based, solar photovoltaic projects in Malawi | Dauenhauer, Peter; Frame, Damien; Eales, Aran; Strachan, Scott; Galloway, Stuart; Buckland, Hannah | Energy, Sustainability and Society; Vol. 10. (2020)
- J. Leary, M. Czyrnek-Delêtre, A. Alsop, A. Eales, L. Marandin, M. Org, M. Craig, W. Ortiz, C. Casillas, J. Persson, C. Dienst, E. Brown, A. While, J. Cloke, K. Latoufis |Finding the niche: A review of market assessment methodologies for rural electrification with small scale wind power | Renewable and Sustainable Energy Reviews | Volume 133 | 2020 | 110240 | ISSN 1364-0321

1.4.2 Peer Reviewed Conference Publications

- Social Impacts of Mini-grids: Towards an Evaluation Methodology | Eales, Aran; Walley, Luke; Strachan, Scott, Frame, Damien | IEEE PES PowerAfrica Conference, Cape Town, South Africa (2017)
- Feasibility study for a solar PV microgrid in Malawi | Eales, Aran; Archer, Lloyd; Buckland, Hannah; Frame, Damien; Galloway, Stuart. | 53rd International Universities Power Engineering Conference IEEE, (2018).
- Assessing the Feasibility of Solar Microgrid Social Enterprises as an Appropriate Delivery Model for Achieving SDG7 | Eales, Aran; Strachan, Scott; Frame, Damien; | Energising the UN Sustainable Development Goals through appropriate technology and governance Conference, Leicester (2019)
- Sustainable Delivery Models for Achieving SDG7: Lessons from an Energy Services Social Enterprise in Malawi |Aran Eales, Damien Frame, Will Coley, Edgar Bayani, Stuart Galloway, (2020) In 2020 IEEE Global Humanitarian Technology Conference (GHTC)
- Techno-Economic Analysis of PAYG Productive Uses of Energy in Malawi | Smith, Kyle; Eales, Aran; Frame, Damien; Galloway, Stuart | IEEE Global Humanitarian Technologies Conference, Seattle (2019)
- Electricity access options appraisal in Malawi: Dedza district case study | Eales, Aran; Frame, Damien; Dauenhauer, Peter; Kambombo, Blessings; Kamanga, Philimon | 2017 | Paper presented at 2017 IEEE PES PowerAfrica Conference, Accra, Ghana.
- Experiences from deploying solar PV energy businesses in rural Malawi | Frame, Damien; Dauenhauer, Peter; Eales, Aran | Energising the UN Sustainable Development Goals through appropriate technology and governance Conference, Leicester

1.4.3 Technical Reports

- Market Assessment for Locally Manufactured PV-Wind Hybrid Systems in Malawi. / Sumanik-Leary, Jon; Org, Madis; Little, Matt; Persson, Jon; Kalonga, Clement; Eales, Aran; Yona, Louis;

Kaunda, Morton; Kamwendo, Maxwell; Bayani, Edgar. Glasgow: University of Strathclyde, 2016. 125 p.

- Social Impact of Mini-grids: Monitoring, Evaluation and Learning | Eales, Aran; Walley, Luke; Colenbrander, Emma; (2018). University of Strathclyde
- Towards Energy Access for All: Planning for Impact | Rajagopal, Wykes, S., & Eales, A. | Low Carbon Energy for Development Network (LCEDN), Loughborough (2019)
- Malawi District Energy Officer Blueprint: Recommendations Paper. | Buckland, Hannah; Eales, Aran; Brown, Ed; Cloke, Jon; Blanchard, Richard; Yona, Louis; Zalengera, Collen; Batchelor, Simon; Sieff, Richard; Nyirenda, Estrida; Bayani, Edgar. Glasgow: University of Strathclyde, 2017. p. 1-15.
- Renewable Electricity for Productive Uses: A Community Toolkit for Sub-Saharan Africa. | Eales, Aran; Buckland, Hannah; Frame, Damien; Strachan, Scott; Suwedi, Memory; Unyolo, Berias; Gondwe, Chawezi; Bayani, Edgar. 100 p. Edinburgh. 2017, Toolkit.

2 Literature review: facilitating human and economic development with Solar Microgrid Social Enterprises

The initial purpose of this chapter is to provide a critical review of the various literatures relating to key perspectives on the current state of energy access and methods to achieve it, focusing in particular on the role of solar microgrids and social enterprise business models. Subsequently, relevant literature is reviewed relating to current understanding of the social impact of electrification and methods for measuring it. As the output of this thesis is ultimately a planning tool to inform microgrid business models and their socio-techno-economic design, a review is also presented of academic and industry research and availability of planning tools currently available to practitioners and policy makers to aid microgrid design and deployment.

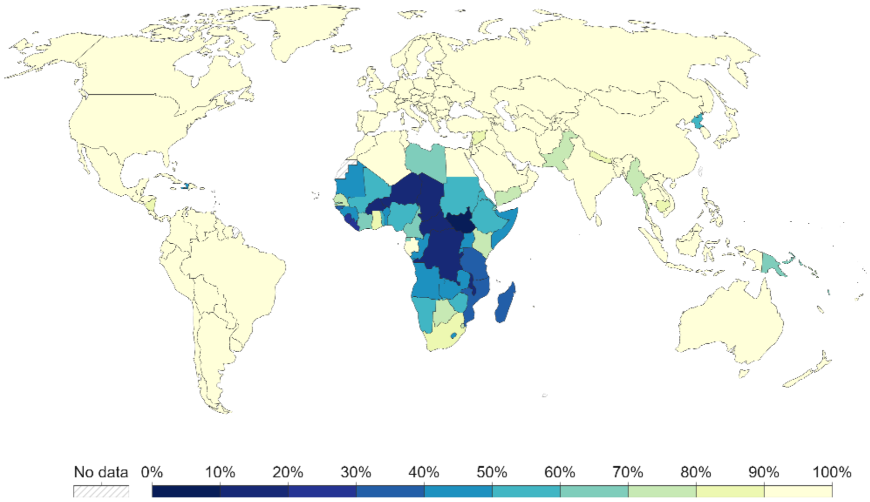
This chapter presents a critical review of these different literatures and in turn highlights how this research seeks to contribute towards the development of these approaches, particularly with respect to improving understanding of financial sustainability of SMSE, and the social impact they provide to communities they serve. Consequently, this chapter acts as a necessary precursor to Chapter 3 where the methodological framework this research employs in order to address the research questions is presented. The literature review presented in this chapter has been used to inform the methods and context required for the research area, framing the research in the body of existing literature and highlighting the novelty of the methodology and results obtained. The landscape review has been mapped through searches in Google Scholar, using relevant search terms including “access to energy”, “mini-grid”, “microgrid”, “planning tools”, “design”, “business modelling” and “Sub-Saharan Africa”, drawing on a wealth of information including journal papers, policy briefs industry reports.

2.1 The role of solar PV mini-grids in the global energy access challenge

2.1.1 The energy trilemma

Globally, approximately 770 million people currently lack access to electricity [2], predominantly in Sub-Saharan Africa (SSA). Electricity plays a pivotal role in improving health, education services, and increasing productivity in underdeveloped areas highlighted by the focus of the United Nations Sustainable Development Goal 7 (SDG7): universal access to affordable, reliable, sustainable, and modern energy [28]. The World Economic Forum defines energy poverty as the lack of access to sustainable modern energy services and products [29]; energy poverty can be found in all conditions where there is a lack of adequate, affordable, reliable, quality, safe and environmentally sound energy services to support development. Energy poverty constrains human and economic development, and access to electricity is a clear and un-distorted indication of a country's energy poverty status.

Accordingly, electricity access is increasingly at the forefront of government priorities, especially in the Global South. Figure 1 shows the percentage of population globally with access to electricity in 2022, according to the World Bank, which collates electrification data from industry, national surveys and international sources [30] [4]. The figure shows clearly that Africa has the furthest to go in achieving universal energy access.



Source: World Bank

OurWorldInData.org/energy • CC BY

Figure 1 Global Access to Energy 2022 (%) [30]

Figure 2 shows that access to electricity has been increasing steadily over the last two decades, with the share of the population with access to electricity for the world increasing from 72.7% in 1998 to 89.6% in 2018. For Least Developed Countries, the rise has been more significant, increasing from 19.2% in 2000 to 51.6% in 2018.

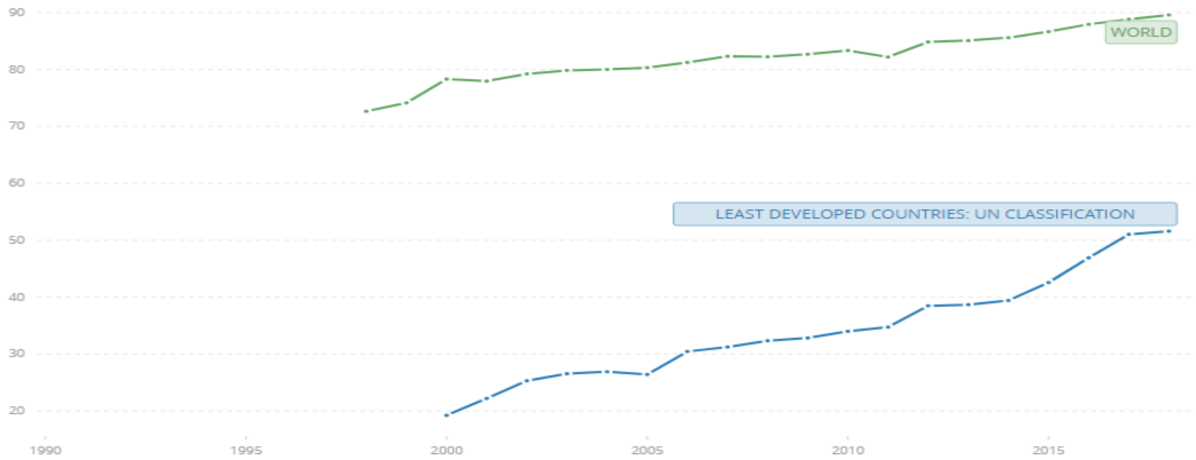


Figure 2 Global and Least Developed Countries access to electricity (% of population) [4]

Figure 3 which shows the number of people without access to electricity broken down into regions, indicates that despite electrification efforts, due to population growth the number of people in SSA without access to electricity actually increased from 400m in 1990 to almost 600m in 2016.

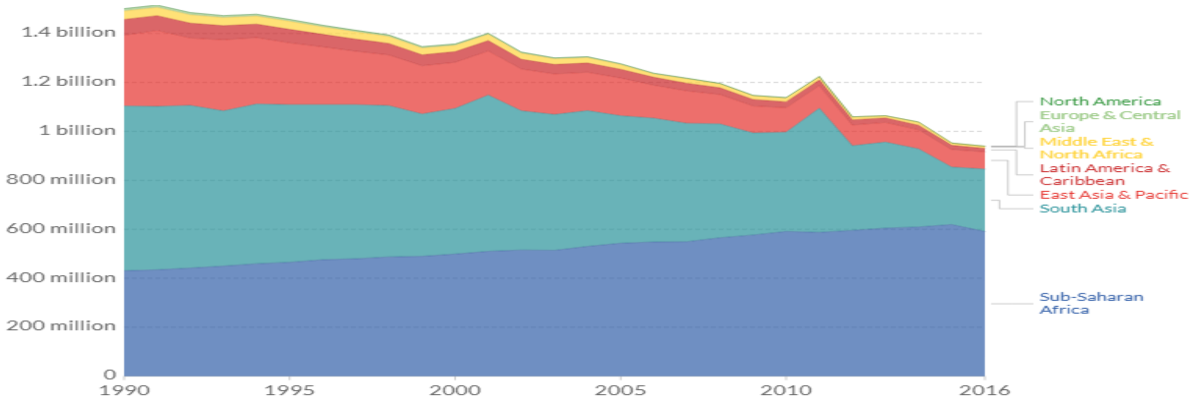


Figure 3 Number of people without access to electricity [30]

A reliable and secure electricity supply underpins economic growth and community prosperity [31], however electricity generation also can also result in detrimental effects on the environment if reliant on fossil fuels. Climate change currently dominates public discussion on energy, as the climate crisis endangers the natural environment around us and the wellbeing of present and future generations. Climate justice address the fact that low income countries produce the lowest emissions but are most likely to suffer the worst effects of climate change [32]. Energy consumption is responsible for 87% of global greenhouse gas (GHG) emissions [33], however utilising renewable energies from primary or secondary solar power produces significantly less carbon dioxide emissions than fossil fuels.

In addition to providing environmental benefits, the use of renewable resources also enhances energy security. Many countries in the Global South depend on imported fossil fuels such as diesel or coal for a large portion of their electricity generation, exposing their economies to price shocks resulting from the volatility of the price of oil and risks due to supply chain disruption [34]. Conversely, renewable energy technologies relying primarily on local and freely available resources are less vulnerable to price shocks associated with primary energy sources.

In summary, energy is necessary for creating conditions for human development and economic growth, and maintaining reliable electricity services in a low carbon manner and gaining energy security through utilisation of local and resilient energy sources is a key challenge for countries throughout the world, especially those in the Global South. Consequently, rural electrification programs and national electrification agencies in developing countries face the trilemma of providing universal access to electricity for their populations, in a secure and low carbon manner.

2.1.2 The rise of solar PV

Solar photovoltaics (PV) is the fastest growing renewable power source globally, with an annual growth rate of cumulative solar energy capacity averaging 25% over the last five years [35]. According to a market assessment of solar PV in Africa module prices fell rapidly from the end of 2009, to between USD 0.52-0.72/watt in 2015 [13], currently estimated at USD 0.24/watt in 2023 [36]. At the same time, balance of system costs have also declined, resulting in the global weighted average cost of utility-scale solar PV falling by 62% between 2009 and 2015 and projected to decline by 57% from 2015 levels by 2025 [13].

The cost trend of crystalline silicon photovoltaic cells since their introduction in 1970's has followed an exponential reduction described as the Swanson effect as shown in Figure 4. The price drop has been achieved through both significant expansion of module manufacturing capacity in China and a fall in the price of polysilicon, the raw material used to manufacture the PV wafers cells. [37].

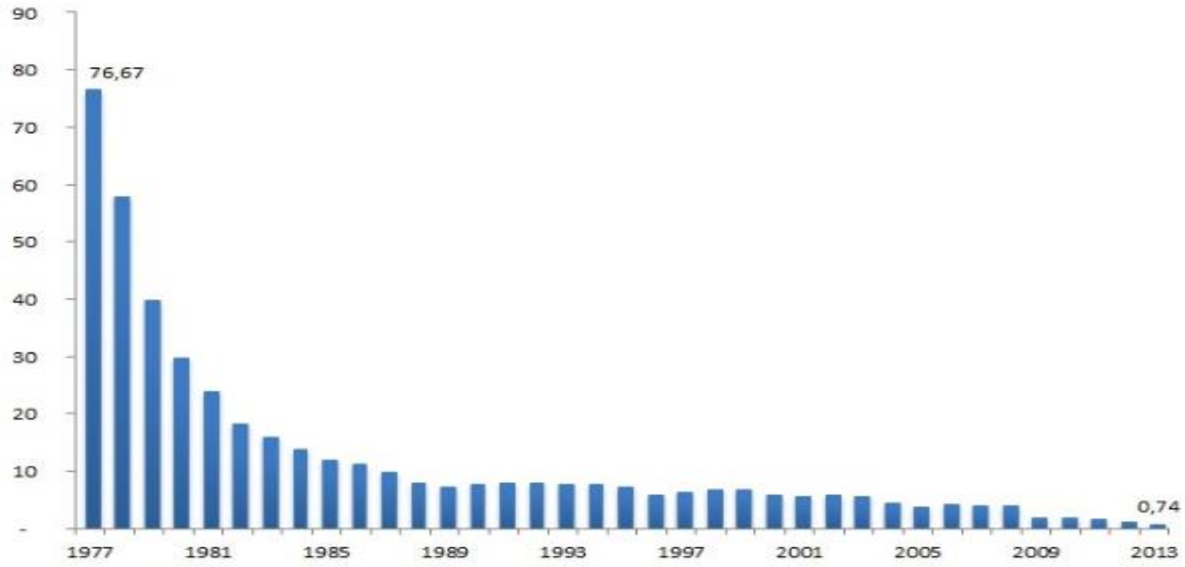


Figure 4 The Swanson effect: Price of crystalline silicon photovoltaic cells, $ per watt [37]

In parallel, and related to the reduced costs trends, solar PV has experienced an exponential growth globally over the last two decades. From 2005 total solar global generation has increased exponentially to 700 TWh, with the most significant increase observed in Asia Pacific, and the least in Island States and Africa, as shown in Figure 5.

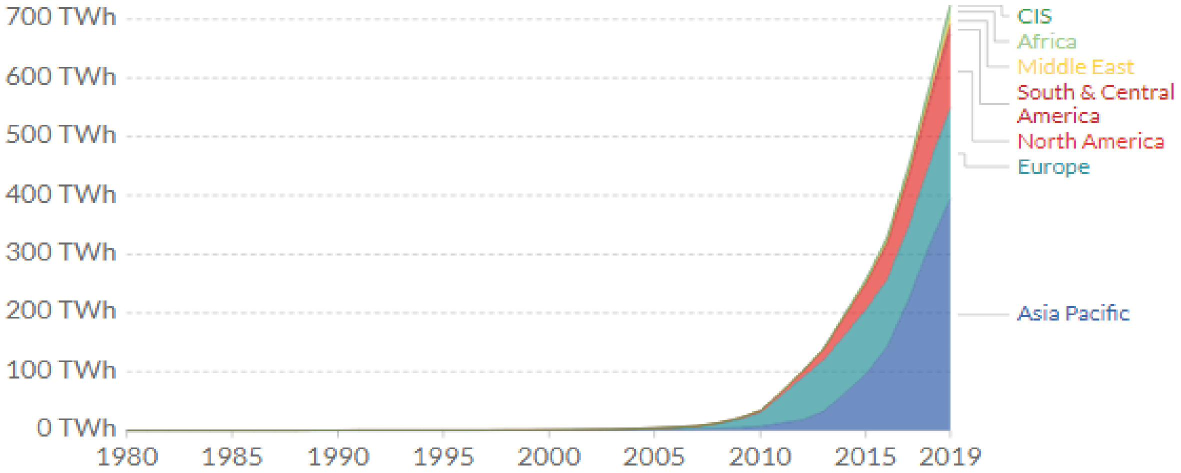


Figure 5 Solar energy generation per year by region [38]

Due to the modularity and scalable nature of solar PV, coupled with low maintenance requirements and high solar resource availability on the continent, solar PV provides a significant opportunity to provide energy access at multiple scales and energy access tiers.

2.1.3 Solar PV and energy access tiers in Sub-Saharan Africa

42.8 % of the population in SSA had access to electricity in 2016, meaning that more than 600 million people live without electricity, including more than 80% of those residing in rural areas [39]. Electricity access is not binary. To capture the multi-dimensional nature of electricity access, a multi-tier framework (MTF) was proposed by SE4All [4], captured in Figure 6. The MTF offers five tiers of electricity access based on parameters of capacity, duration, reliability, quality, affordability, legality and health and safety. Tier 0 represents the use of kerosene or candles while tier 5 represents grid access.

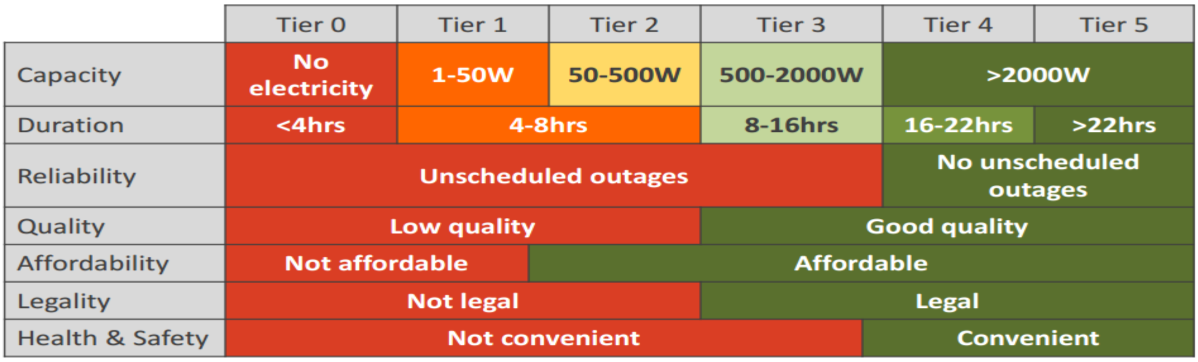

<table>
<tr><th></th><th>Tier 0</th><th>Tier 1</th><th>Tier 2</th><th>Tier 3</th><th>Tier 4</th><th>Tier 5</th></tr>
<tr><td>Capacity</td><td>No electricity</td><td>1-50W</td><td>50-500W</td><td>500-2000W</td><td colspan="2">>2000W</td></tr>
<tr><td>Duration</td><td><4hrs</td><td colspan="2">4-8hrs</td>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

Figure 6 Energy Access Tiers [40]

It is estimated that off-grid solutions are necessary to supply 40-63% of the additional generation needed in developing countries to achieve universal electricity access by 2030 [41]. In many areas of SSA, grid expansion has occurred at a faster pace than accompanying generation capacity, resulting in frequent blackouts and grid unreliability. Frequently, grid connected users have redundant double or triple infrastructure, backing up the grid with diesel generators, solar home systems or minigrid connections [42].

Solar PV electrification supports all three dimensions of sustainable development: economic, social, and environmental. It is estimated that 740 million people, primarily in Sub-Saharan Africa and South Asia, will benefit from solar products by 2022 [43]. The common types of electricity access in Sub-Saharan Africa (SSA) that utilise solar PV, categorised into the SE4All tiers is outlined in Table 1.

Table 1: Solar electricity access currently available in SSA, ordered in terms of size with identified customer types

SE4ALL Energy Access level	Common solar electricity access type in SSA	Description	Size	Customer
TIER 0 -1	Pico-Solar Products Solar Lanterns	Battery powered products. One-off purchase. Lighting Africa is a regulator	Small, personal use <20Wp	The majority of people in SSA use pico-solar products [44] [45] [46]
TIER 2-3	Solar Home systems	PV systems comprising of panels, charge controller, batteries, inverter. Personal household use off-grid or grid connected back-up power	Small personal home systems (of the order of .1kW to .5kW) usually powering lighting and some small loads, such as phone charging.	Off-grid homes. Back-up for national grid users (more purchases in 2017 due to frequent grid black-outs)
TIER 4	Nanogrids Microgrids Community systems	PV systems comprising of panels, charge controller, batteries, inverter. Community use off-grid or grid connected back-up power	Small community uses such as school lighting (of the order of .1kW to .5kW) usually powering lighting through the night and some small loads, such as phone charging.	Off-grid communities. Back-up for national grid
TIER 4-5	Mini-grids	PV systems comprising of panels, charge controller, batteries, inverter. Community use but externally managed off-grid or grid connected back-up power	Medium/Large community and customer use	Off-grid communities. Businesses and public infrastructure
TIER 5	National grid (with black-outs on a daily basis)	National grid powered by Hydro/ Diesel/ Larger generators.	Medium/Large customer and industrial use	Households and businesses

Tiers 1 to 3 can generally be provided by Pico solar products (PSP) or solar home systems (SHS). PSP are small independent plug-and-play appliances providing light and/or additional electrical services, like charging mobile phones as well as powering very small-scale appliances such as radios [47]. SHS kits are complete off-grid systems, independently installed for each customer typically including rooftop mounted PV module(s), batteries, charge controller and energy-efficient LED lights [22].

Mini-grid scale solutions lie between the option of large-scale national grid extension and small stand-alone solutions such as pico-solar products and solar home systems [48], and thus fill the gap offered through servicing tiers 3 -5. Mini-grids and can also effectively serve communities close to the grid in more developed countries, where 'grid-tied' or 'interconnected' mini-grids can deliver high-quality service while reducing grid demand, easing congestion as well as national electrification budgets [49]. With such promise and potential, there has been substantial interest in implementing mini-grids or community-based systems in developing countries, particularly in SSA [50].

2.1.4 Mini-grids for rural electrification

Mini-grids have become a viable option for providing reliable and high-quality electricity to rural populations. In 2020, 47 million people worldwide were already connected to 19,000 mini-grids, of which at least 2,577 are operational clean energy mini-grids [11]. A total of 180,000 additional mini-grids need to be built to supply electricity to 440 million people if the overarching objective of universal access to electricity by 2030 is to be achieved [51]. The International Renewable Energy Agency (IRENA) estimates that mini-grids will be the best solution for over a third of the global population currently living without electricity access [41], and the International Energy Agency estimates that they will provide 48% of the additional generation needed to achieve universal electricity access by 2030 [27]. The mini-grid market is on the rise, mainly due to decreasing costs of renewable energy technologies and battery storage.

The decentralized nature of mini-grids has several inherent advantages over traditional centralized infrastructure, including improved economics, technical performance, environmental sustainability, and regional equity in the context of rural electrification [52]. Rural electricity demand is generally low, and the energy losses incurred through grid transmission and distribution often don't justify the cost of building long and extensive power line infrastructure to remote areas, often making decentralised solutions such as mini-grids the most cost-effective solutions to delivering electricity to these areas [53] [54], [55]. Indeed, without a decentralized approach to expanding electricity access, it is likely many isolated communities located far from existing grid infrastructure will be left without a connection for decades to come.

According to the African Minigrids Developer Association, mini-grids currently offer about a third of the price of grid utility installed in the same location, and capex costs have fallen in terms of average price per connection from $1,555 to $733 which is radically lower than national utilities in rural areas [56]. Figure 7 shows how the unsubsidised cost ranges for renewable energy mini-grids has fallen sharply since 2005 and is predicted to follow a decline to 2035.

Further, unlike other decentralized technologies such as solar home systems, mini-grids provide higher tiers of energy access and can be more easily integrated into larger grids in the future when economic development takes hold, the central grid expands, and/or demand for electricity rises [57]. Mini-grids connected to the main grid have the ability to feed excess electricity into the network or draw electricity to meet shortfalls, allowing for aggregation of loads and generators on a larger scale that unlocks greater economies of scale and more efficient power system management [58]. Security is further enhanced by maintaining the ability to operate mini-grids in an islanded mode once interconnected, giving potential for distributed energy generation resources in semiautonomous microgrids to avoid rolling blackouts often associated with centralized grid networks in developing countries.

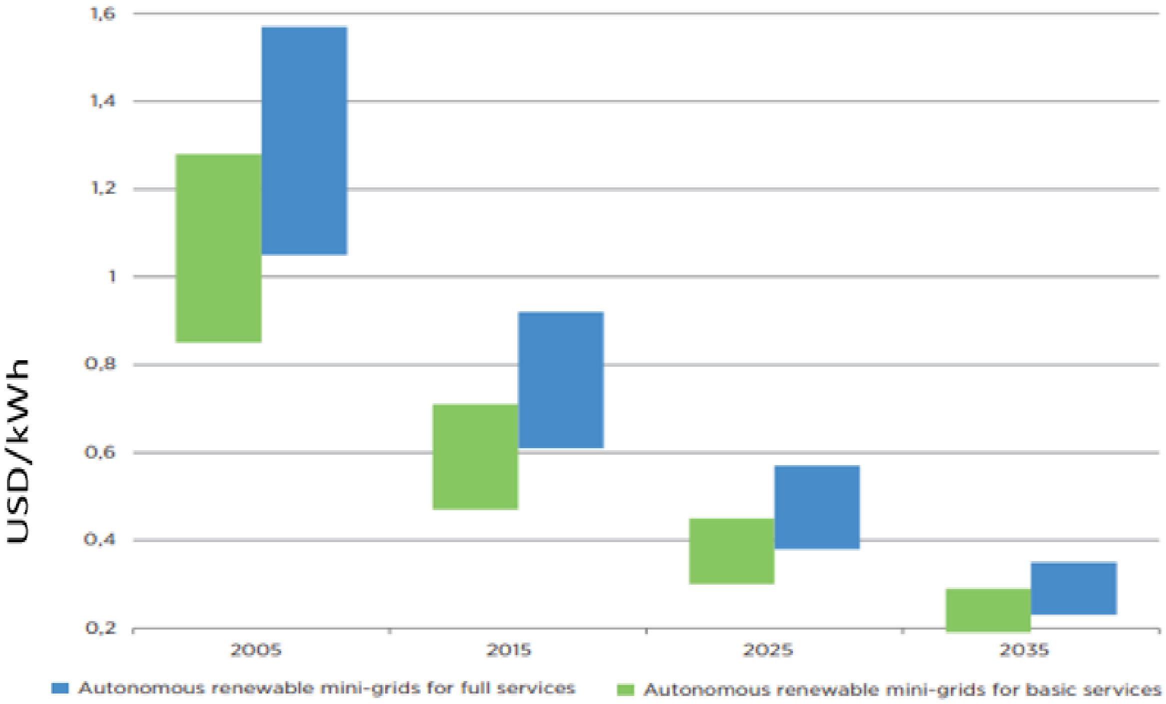


Figure 7 Unsubsidised cost ranges for renewable mini-girds from 2005 to 2035 for a 100% renewable energy community system (53)

2.2 Solar microgrids

2.2.1 Microgrid definitions

A nanogrid, microgrid or mini-grid is a term used to describe a network consisting of a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the main grid [59]. In simple parlance, these terms describe a system that links together demand points within a limited area without connection to the main grid, for the user an experience that is something in between a main grid experience and a standalone experience in terms of quality and quantity of power.

The categorisation as nano, micro and mini refer to their installed generating capacity, the number of households they serve, geographic area covered and their integration into the main grid. Various definitions exist, outlined in Table 2, but a unifying set of defining characteristics is yet to emerge.

Table 2: Minigrid, Microgrid, and Nanogrid definitions

Source	Definition
Mini-grid	
Energypedia [12]	A set of electricity generators and possibly energy storage systems interconnected to a distribution network that supplies electricity to a localized group of customers. They involve small-scale electricity generation (10 kW to 10MW) which serves a limited number of consumers via a distribution grid that can operate in isolation from national electricity transmission networks.
United Nations Framework Convention on Climate Change (UNFCCC)	A generation and distribution system a power rating below 15MW and disconnected from larger electric grids.
IRENA [41]	Renewable energy mini-grids are a form of integrated energy infrastructure with distributed energy generation resources and loads. They provide autonomous capability to satisfy electricity demand through local generation, mainly from renewable energy sources.
World Bank	Isolated, small-scale distribution networks typically operating below 11 kilovolts (kV) that provide power to a localized group of customers and produce electricity from small generators, potentially coupled with energy storage system.
Microgrid	
International Electro technical Commission. 2017-12-15 [60]	group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is able to operate in either grid-connected or island mode" Note 1 to entry: This definition covers both (utility) distribution microgrids and (customer owned) facility microgrids.
US Department of Energy [61]	A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. A remote microgrid is a variation of a microgrid that operates in islanded conditions
IRENA [57],	as an energy generation and supply system with maximum capacity of 100 kW having capabilities of managing local energy supply
Nano Grid	
Lawrence Berkeley National Laboratory[62]	A nanogrid is a single domain for voltage, reliability, and administration. It must have at least one load (sink of power, which could be storage) and at least one gateway to the outside.
Lawrence Berkeley National Laboratory[62]	A small electrical domain connected to the grid of no greater than 100 kW and limited to a single building structure or primary load or a network of off-grid loads not exceeding 5 kW, both categories representing devices (such as DG, batteries, EVs [electric vehicles], and smart loads) capable of islanding and/or energy self-sufficiency through some level of intelligent DER management or controls

Often, microgrid is used as the term for where a system has an interactive and functional relationship between the central grid and its users, allowing it to use the services of the central grid, and can support services to the grid when it’s beneficial to do so. Although a mini-grid can also have this functionality, it is generally more understood for mini-grids to operate autonomously from the grid. Additionally, by the definition of the name, a microgrid suggests a smaller system than a mini-grid.

The focus of this thesis is in SSA, where the target populations to provide energy access are generally small sparsely populated communities and villages. The scale of grid is necessary smaller to cater for these smaller remote communities, which is why micro is preferred over mini. Additionally, it is recognised that the grid will eventually arrive to these communities and following the trend that microgrids are understood to have grid connected functionality is also intentional. Accordingly, the following definition is given for solar microgrids as a reference for the rest of this thesis:

"A solar microgrid is an electrical network with solar PV generation less than 100 kWp, providing supply through a distribution network, either autonomously, connected to other microgrids, or to a main grid."

2.2.2 Benefits and limitations of solar microgrids

The energy access gap at TIER 4-5 is an obvious opportunity for improving energy access and microgrids at a community level bridges the gap between low electricity usage and national grid extension. Microgrids offer economic benefits as connections become cheaper with economies of scale, and customers don't use electricity at the same time so demand per customer is reduced and in general sharing electricity has economic and efficiency benefits.

Hazelton [63] conducted a preliminary literature review of the benefits and risks presented to communities by PV hybrid microgrid systems. The paper found that the most commonly identified benefits are reduced cost and provision of improved electrical services (more reliable and higher capacity), with opportunity for rural enterprise, strengthened community and local capacity building also cited. Other advantages of microgrids over stand-alone systems include improved reliability and security of supply, economies of scale, improved utilisation factor, load factor, and diversity factor, all leading to reduced cumulative installed capacity, less generation for peak demand compared to that required in a village consisting of highly distributed stand-alone systems, and therefore lower energy cost [64]. Microgrids can contribute to awareness raising and involvement of local communities through development of a common project and allowing the use of higher power electrical appliances and thereby encouraging productive activity.

Disadvantages include risk of all customers being disconnected in the event of plant failure, (although reliability issues associated with a microgrid is less than that associated with off-grid stand-alone systems [57], and more complicated regulatory, organisational and technological organisation than lower power competitors such as solar home systems [65]. Major risks identified in [63] included incorrect system sizing due to load uncertainty, challenges related to community integration, inappropriate business models and risks associated with geographical isolation. Figure 8 compares solar microgrids to other technologies in terms of tiers of electricity, supply, availability, and indicative use.

Figure 8: Comparing Solar Microgrids to other technologies [63]

Technology	System Power (W)	Areas reached by one system	Price ($/kWh)	Distribution channel/provider	Services provided	Maintenance	Durability (life expectancy of product)
Kerosene	N/A	1 room	$20 – 45 (kWh equivalent)	Local supplier	Light	Easy, owner	5 litres per night
Dry Cell	~5W	1 room		Local supplier	Light, radio	Easy, owner	
Solar Lanterns	~10W	1 room	$2	Retail stored	Light	Easy, owner of product	3-5 years
Solar Home systems	50 – 100W	1 household	$60	Retail stores and enterprises	Light, USB charging	Moderate, owner or product provider	Batteries: 5 years, PV modules: 20 years
Solar Microgrids	100W + per village	1 village (50 – 500 households)	$30	Enterprises and other organisations	Light, USB charging outlets, Industry	Difficult, owner or technician	Batteries: 5 years, PV modules: 20 years
Other microgrids (Wind)	100W + per village	1 village (50 – 500 households)	$60	Enterprises and other organisations	Light, USB charging outlets, Industry	More difficult: owner or technician	Batteries: 5 years, PV modules: 20 years
National Grid	1000W – 2200W per home	1 country	$10-20	Government	Light, outlets, Industry	Most difficult: Government	Indefinite

2.2.3 Technical overview of solar microgrids

This section provides an overview of key technical components including generation, storage, conversion, and connection to the main grid. As shown in Figure 9, microgrids comprise power generation technology, storage to account for intermittent renewable resources, a distribution grid providing electricity to load demand (customers), and protection and control elements. Microgrids also have the option of interconnecting with other microgrids and connecting to a central grid network.

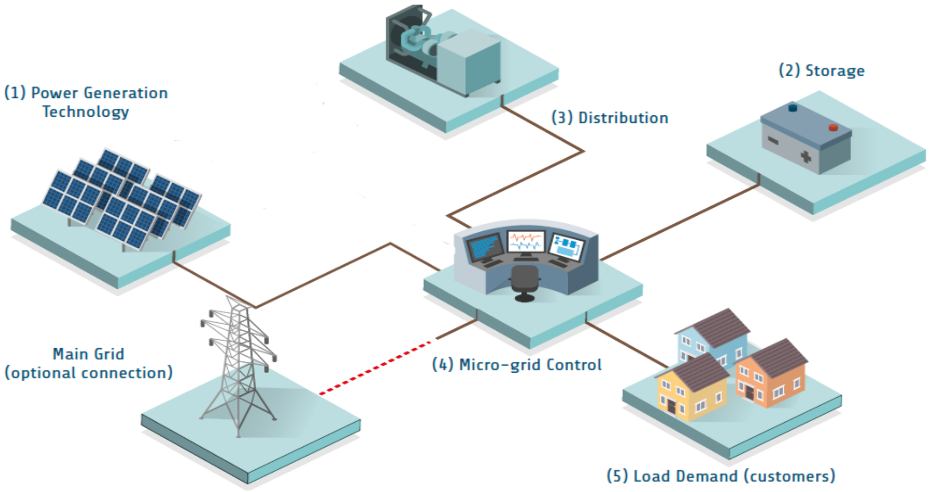


Figure 9 Micro-grid components Adapted from [64]

2.2.3.1 Generation

Common generation technologies applicable for renewable energy microgrids are solar PV, wind, hydro and biomass applications [41], but the focus of this thesis is microgrids powered by low-cost silicon-based polycrystalline solar PV modules. Due to their remote locations, utilising solar PV for power generation is central to the functionality and value offered by solar microgrids. PV modules can be mounted on roofs, ground mounted, or on a shipping container. The latter is increasing in popularity due to ease of transport, and ability to redeploy if the projects faces economic challenges. The option to redeploy also make the technology resilient to climate risks, as it can be moved if faced with flooding or wildfires. Additional to the PV modules, a project planner must therefore consider mounting structures, DC cabling, switching components and integration into storage and conversion technologies [64].

2.2.3.2 Storage

Storage enables microgrids to utilise energy when no generation is available, especially important for solar microgrids to provide domestic evening loads. Additional advantages include an increase in the share of renewable energy, the ability to provide continuous power, lowering peak demand for power, ramping and smoothing load and generation, and lessening the impact of long-term and short-term fluctuations in renewable energy [66]. Typical storage mechanisms involve battery banks which are charged as excess energy is produced [67]. Due to the high upfront costs and replacement needs that vary with each storage option, storage currently accounts for a significant portion of the costs associated with the deployment and operation of renewable mini-grids, which can range between 20% and 40% of total CAPEX [68].

Lead-acid batteries, with sub-types such as Absorbed Glass Mat (AGM), NiCD, Flooded, and gel, have been the dominant technology for electrochemical storage for decades. However, they have the disadvantages of being physically heavy, having a long recharging cycle (8 hours), requiring fewer lifetime recharges, and requiring periodic maintenance [69]. Lithium-ion batteries, which have a higher energy density, are more resilient, and have a longer life cycle, are now providing competition as a preferred alternative to the more common lead acid batteries, and their market share is expected to grow in the coming decades [70].

2.2.3.3 Conversion

Conversion enables a solar microgrid to move energy around the network. The typical conversion required is between the Direct Current (DC) energy generated by PV modules and stored in batteries and the Alternating Current (AC) distribution networks. Power conversion between different types of electric charge can be classified as converters (DC-to-DC, AC-to-AC), rectifiers (DC-to-AC), and inverters based on the input and output currents (AC-to-DC). Grid-following, grid-forming, and dual-mode inverters are the three types of power inverter technologies. Grid-forming inverters are the most common in solar microgrids because they can create an AC grid, whereas dual-mode inverters are more expensive and combine the benefits of grid-following and grid-forming and serve as the main grid interconnection point [41].

2.2.3.4 Control

Protection strategies, intelligent decision making, and data collection, whether by specific devices or by multiple devices working in tandem, are all part of a solar microgrid's control and monitoring functionality. They can ensure optimal solar energy integration into the microgrid, operational transparency and economic reliability, as well as maximum microgrid energy efficiency [41]. By enabling communication between the devices that provide these services, solar microgrid management hardware and software serve as an interface between energy generation and consumption.

2.2.3.5 Distribution

Energy is transferred from the point of production to the point of use or consumption via distribution networks. Microgrids can run on AC, DC, or a combination of the two, known as a hybrid AC/DC system. The geographical span of the area to be serviced will influence the type of system (AC, DC, single phase, three-phase), which has implications for the cost of the network, the type of end-user load the network can supply, and how usage can be recorded and metered to enable billing of consumers. The distribution network in a solar microgrid is typically a single-phase AC network that connects the generation hub to the customer premises. Overhead distribution via wooden or concrete poles is less expensive, but more vulnerable to tampering, than buried or underground cabling. The connections typically connect a building to a distribution board that contains MCB breakers, earthing protection, and wiring for lighting and AC sockets [71]. Microgrids that use DC distribution networks can save money by eliminating the need for inverters; however, the distances the distribution grid can serve are shorter, and customers require DC appliances that are less commonly available [72]. Additionally, while applications of DC microgrids are limited to low power appliances such as efficient LED lighting and mobile phone charging, AC systems allow widespread availability of appliances.

2.2.3.6 Metering

To enable and enforce tariff payments on microgrids, energy meters are commonly used [73], which present several advantages by allowing consumers to have an accurate record of consumption and therefore incentivise energy conservation and efficiency measures. Meters can also substantially reduce grid energy consumption, avoiding overload and/or the system reaching capacity. However, they also come at a cost, influencing global microgrid costs or increasing connection fees.

Next-generation energy meters go beyond simply measuring end-user energy consumption, increasingly playing a demand-side management role and capable of limiting consumer energy consumption, which is beneficial microgrids dependent on storage [74]. A wide range of meters are available with different functionalities and payment methods: prepaid or pay-as-you-go, post-paid, service-based, non-flat tariff schemes (energy based or power-based), and those accompanied or unaccompanied by software [75].

2.2.3.7 Grid Connection

Coupling microgrids with a larger centralized grid through a grid-tie inverter can provide high levels of reliability, allowing the central grid to be used when microgrid supply is inadequate. However, in the absence of regulations for feed-in tariffs or net-metering which is the case in most African countries currently, fully-autonomous microgrids are easier to implement and most common [76]. With on-grid systems, intelligent control facilitates switching to or from the grid based on consumption and energy storage levels, as well as ensuring that generating equipment functions at predefined operating points and within set limits [77].

2.2.4 The space for solar microgrids in wider rural electrification strategies

Figure 10 illustrates how parameters related to the geography, density and community size influence choice of energy access solutions. Specifically, the diagram illustrates how the cost of access for stand-alone (SHS and PSP), microgrid and national grid extension varies with these parameters.

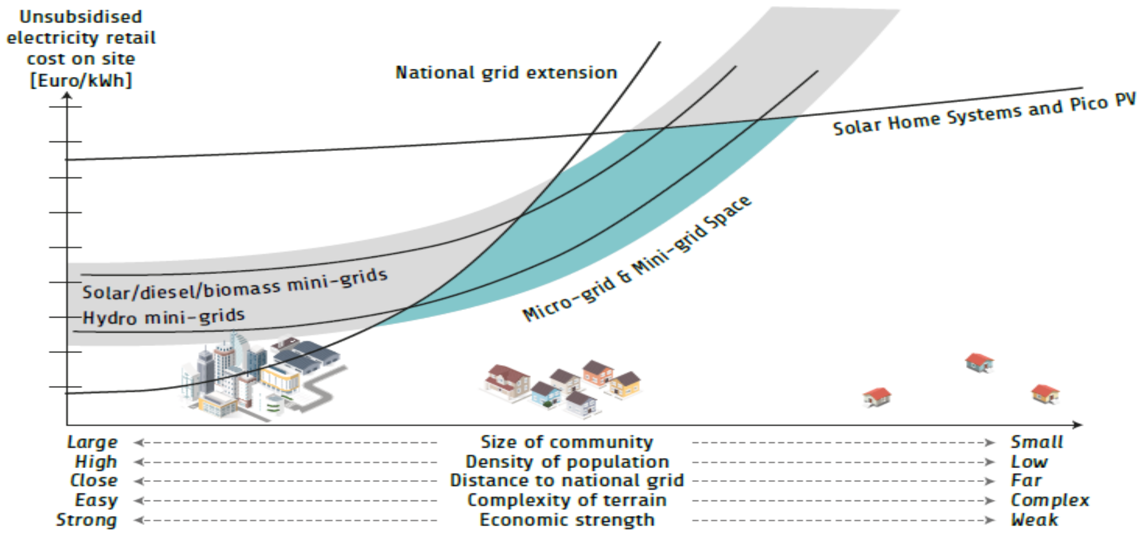


Figure 10 Micro/Mini-grid space compared to alternatives [78]

The cost of stand-alone systems increases only moderately and is generally invariant to the parameters. National grid extension is justified for communities that are large, dense and close to the grid, and the cost of grid extension increases exponentially as the distance they have to cover increases. As communities become smaller, less dense and more dispersed or displaced from the grid, the cost of grid extension becomes significantly higher than either stand-alone or mini grids. In large, dense communities that are close to the national grid, micrograms may be more expensive than grid-extension but are more economical than stand-alone systems. As communities decrease in size and become less dense, microgrids start to make economic sense relative to grid extension. As communities become smaller and more dispersed, stand-alone systems are a better option. As such, microgrids find their space when grid extension is not economically viable, where the population density and community size leverages economies of scale over stand-alone approaches [78].

2.2.5 Business models for solar microgrids

A microgrid delivery or business model is defined as the method by which microgrids are deployed and operated. The definition of a business model as defined by [79] is a system that identifies who its customers are and engages with their needs, delivers satisfaction and monetizes its value. For microgrids, it answers questions of who delivers and installs the microgrid, who pays for the microgrid assets and by what means, who owns the assets and who is responsible for replacement or extension investments and who operates the microgrids and performs customer service [80]. The sustainability of off-grid microgrid projects is therefore largely dependent on its ability to cover costs and maintenance which is defined in its business or delivery model.

2.2.5.1 Ownership and operation models

There are four main microgrid operation models, differing in their approach to deployment and organisation. The success or failure of microgrid operation models will be context specific and will depend on many different variables such as: the environment; geography; socio-economic variables; as well as the policy/regulatory environment [81]. The five main microgrid operation models are:

- **Utility operated**: A government or national utility contracts a private company to supply and install microgrids. The national utility subsequently takes over the operation of the microgrids.
- **Energy Service Company (ESCO):** The government finances and owns the microgrid assets, which are installed and/or operated by a private company or cooperative. Tariffs charged to electricity customers (plus optional government operating expenditure (OPEX) grant) cover the private operator's costs of operation, including profit.
- **Private with capital expenditure (CAPEX) grant**: The private sector or cooperative microgrid operator finances, installs, owns and operates the microgrid assets, sometimes receiving a CAPEX grant from the government or donor.
- **Hybrid models or split asset:** The distribution network is financed and owned by the government. The private sector or cooperative operator finances, builds, owns the generation assets, and operates the entire microgrid.
- **Community operated:** the minigrid is funded through donor or government capital, with operations and tariff collections conducted by a village energy committee or similar.

Figure 11 shows how the funding level, tariff level and degree of government control varies for these different operating models. Not shown in the figure is community operated microgrids, which have a low tariff level and low degree of government control, however tend to suffer financial sustainability challenges and require ongoing donor funding [82]

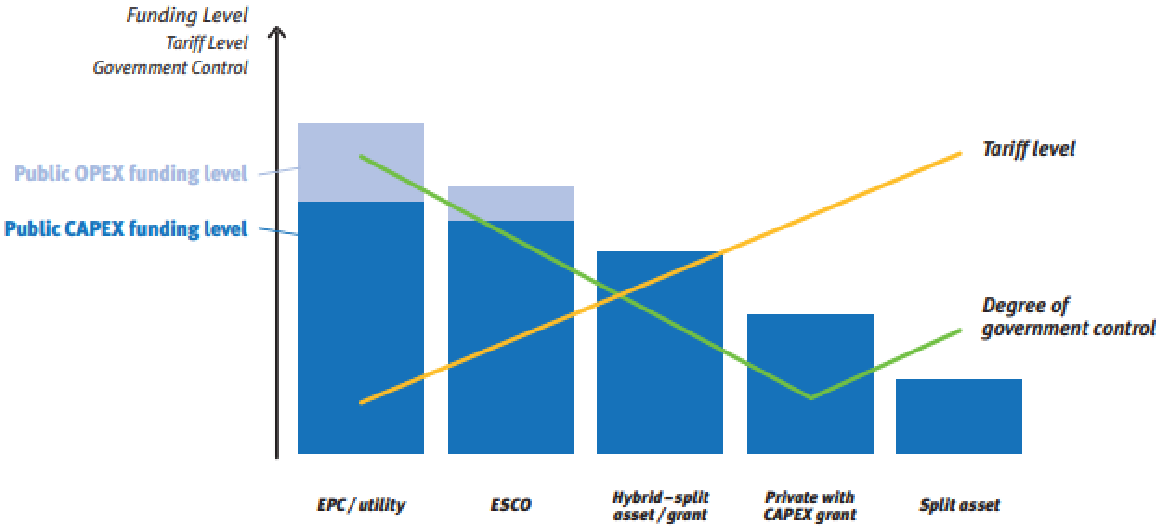


Figure 11 Delivery Models in Dependency of Funding Level, Tariff level and degree of government control [80]

2.2.5.2 Tariff Schemes

According to [78] microgrids earn their revenue through connection fees, electricity sales and grants/subsidies. [55] argues that the revenue a microgrid can earn is reliant on variables like: demand for electricity, the ability and willingness to pay and the tariffs set for consumers. According to a [81], tariffs need to be affordable to customers but also need to be at levels able to generate adequate revenues to meet recurring expenditures and other liabilities, generate an adequate profit, and recover the capital cost of the system to be fully commercial.

Tariffs should be set based on projected demand and in order for the scheme to be viable, should cover all the costs both fixed (e.g. operation, wages) and variable (e.g. maintenance, spare parts, training) of the microgrid plus a margin [83]. A basic rule generally accepted in rural electrification planning is that, regardless of the scheme chosen, a tariff should at least cover the system’s running costs (O&M) in order to ensure the ongoing operation of a system through its lifetime. Cost-based tariffs are also essential to attract project developers when it comes to demonstrating the financial viability of a project [84]. Advanced tariffs often used in mini-grids can vary with the time of use, and include block rates that provide an initial amount of energy at a different rate than subsequent amounts of energy within a period of time.

The ability and willingness to pay is likely to vary depending on the geographic location. Areas with larger population densities tend to have more vibrant economies hence microgrids operating in those areas tend to be more profitable than those operating in remote locations [79]. According to a study done by [85] , revenue collecting in rural areas is challenging as the demand for electricity together with their ability to pay is lower, when compared to urban areas. Ideally, systems designed in rural areas should adopt a pro-poor approach to ensure affordability even for low-income consumers.

2.2.5.3 Load management and productive uses

Certain strategies and technologies should be considered for managing demand on a solar microgrid to ensure efficient and sustainable operation. The use of efficient light bulbs and appliances can greatly improve the overall efficiency of the system, when available and affordable to customers. By both encouraging conservation and reducing peak loads, these measures can allow an existing grid to serve more households and reduce the required initial investment in generation and distribution capacity for a new grid [74].

Selling to larger productive users can be a strategy of securing reliable energy sales because their demand requirements are higher than most domestic customers. Unfortunately, there are relatively few large anchor clients located in rural areas of Africa, and this is one reason why microgrids have yet to make a significant impact on energy access targets, and why it is critical for solar microgrids business models to promote consumption by productive uses of energy (PUE) [86].

2.2.6 Regulatory considerations for solar microgrids

The majority of African governments have signed up to the Africa Renewable Energy [87] as well as the Sustainable Energy for All [3] Initiatives and have commitments to development targets through the African Unions Agenda 2063 as well as the SDGs. The linkages between these policy drivers and solar microgrids, outlined in Table 3, indicate that without the provision of sustainable and resilient energy the attainment of these policy targets and SSA's wider development goals will be compromised.

Table 3: Microgrid contribution to Africa Union Agenda 2062 and Sustainable Development Goals [64]

Agenda 2062 Goal	SDGs	Microgrid Relevance
• Goal 1 – A high standard of Living, quality of life and well-being for all citizens	• Goal 1 – End Poverty in all its forms everywhere in the World • Goal 8 – Promote sustained inclusive and sustainable economic growth, full and productive employment and decent work for all • Goal 11 – Make cities and human settlements inclusive, safe, resilient and sustainable	Enhance socio-economic well-being through improved quality of life, access to public services, job creation/entrepreneurship opportunities and industrialisation enabled by access to energy
• Goal 7 – Environmentally sustainable and climate resilient economies and communities	• Goal 7 – Ensure access to affordable, reliable, sustainable and modern energy for all • Goal 13 – Take urgent action to combat climate change and its impacts	Reduce dependency on fossil fuels Improved reliability of electricity service over national grid Increased access to energy in remote areas
• Goal 10 – World class infrastructure criss-crosses Africa	• Goal 9 – Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation	Promote access to affordable energy based on emerging technologies which are adapted to Africa's needs.

Within the wider policy drivers at a national level for energy access, governments have a variety of policy and regulatory tools to encourage or foster the mini and microgrid sector. An enabling public policy environment is critical to the success of electrification based on microgrids, in particular for rural applications [88]. Conversely, a lack of clear policy, standards and regulatory oversight has been identified by many players in the market, including trade and standards associations, as a stymying factor for the sector, necessitating appropriate rules, regulations and procedures to guide deployment and operation [65].

Regulatory considerations have a significant impact on a microgrid business' ability to thrive, as often the time to make approvals can be prohibitive. These delays affect income projections as electricity cannot be sold until a license is granted, and employing idle staff while waiting for approval can also increase costs, both of which can increase tariffs [89]. The situation is improving, with average mini-grid approval times reducing by 50% since 2015 to 44 weeks [56] as shown in Figure 12. The World Bank estimates that Africa needs 140,000 mini-grids [11] and without radical improvement, this means significant time waiting for approvals, and assuming each site needs a site visit by a government official, a significant resource cost to constrained governments. Proposed methods for improving this situation include bundling, where for example up to 10 sites can be approved at one time, and company approvals rather than site approvals, where companies are allowed to install freely once they have installed a certain amount [56].

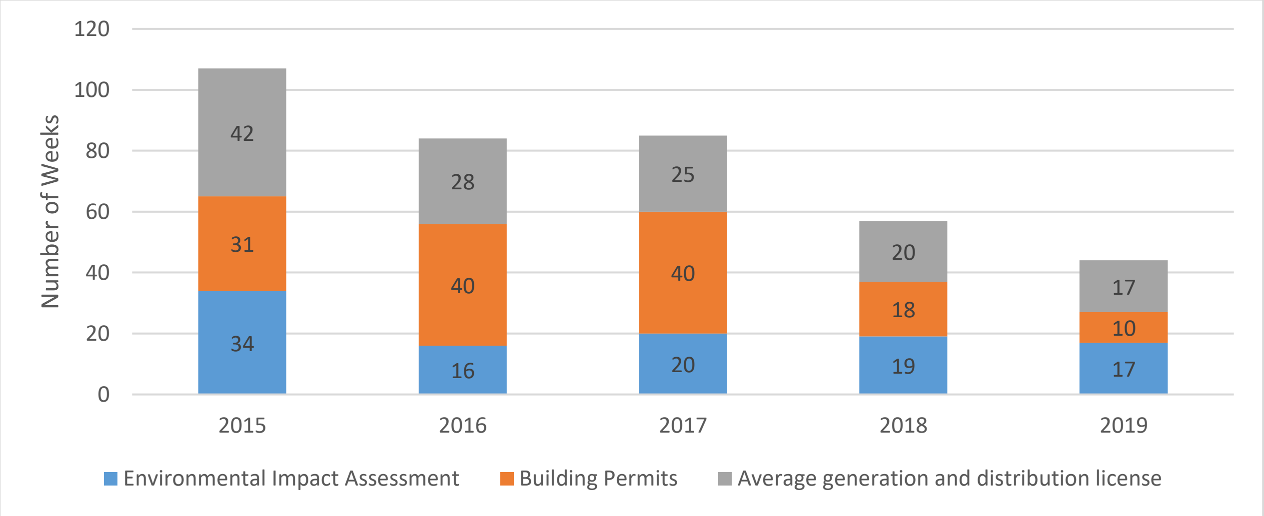


Figure 12 Evolution of mini-grid licensing times [56]

According to UNIDO's clean energy mini-grid policy guidelines [80], sustainable mini-grid business models require scale, and in order to reach scale, all regulatory and administrative processes must be designed to be efficiently applied at large volume. They also suggest that the way in which mini-grids are ultimately deployed, including the degree of private sector involvement, depends on decisions taken by government, and that in order to be sustainable, mini-grids require a comprehensive, long-term political commitment and a stable, reliable policy framework. The importance of effective microgrid policy, and the associated impact this can have on accelerating or stymying a microgrid programme is clear. This thesis aims to be cognisant of this and proposes recommendations throughout to be of utility to both policy and enabling environment decision makers as well as solar microgrid practitioners.

2.2.7 Financing considerations for solar microgrids

Financing considerations for solar microgrids have been an emerging research topic in recent years. As the cost of solar technology continues to decline, the potential for solar microgrids to provide energy access to underserved communities has grown. However, the upfront costs of deploying solar microgrids can be high, and the technology is not always readily available in remote areas. Furthermore, the economic viability of solar microgrids is often challenged by the lack of access to capital, which can be difficult to obtain in rural areas [90]. To address these challenges, practitioners and project developers have trialled a variety of financing mechanisms, including public-private partnerships, crowd-funding, micro-finance programs, and carbon credits. These mechanisms can help reduce the cost of solar microgrids, making them more accessible to underserved communities. Additionally, further research is necessary to identify the most effective financing mechanisms for solar microgrids and to understand the impact that these financing mechanisms can have on the economic viability of the system.

Public financing, patient private financing, and public/private financing are all top-down state and/or market driven approaches to increasing energy access through the financing of solar microgrids. These approaches rely on governments or businesses providing capital or subsidies for the construction and operation of solar microgrids [91]. The benefits of these approaches include lower upfront costs and access to a larger pool of capital. However, there can be drawbacks as well, including lack of flexibility, high transaction costs, and lack of local control. Alternatively, more bottom up, cooperative and social enterprise models have emerged in recent years, providing an alternative to traditional financing models. These models are characterized by increased community involvement and ownership, with local stakeholders actively participating in the design and implementation of solar microgrids [81]. While these models require more upfront effort and resources, they can also provide more autonomy and greater local ownership. As such, further research is necessary to evaluate the benefits and drawbacks of different financing models for solar microgrids in order to identify the most effective approaches.

In developing countries, microgrids as commercial enterprises operated by private entities with independent financial support, that have a goal of being profitable are relatively new and unproven [92]. As such, the market for financing microgrids contains many uncertainties and untested business models [93]. Scarcity of capital has been a barrier to both on-grid and off-grid electrification efforts and governments have sought private sector participation in an effort to close this gap. The need for private investments to meet this target is evident, but small-scale electrification projects are often unattractive for private investors due to unfavourable risk-return profiles and small investment volumes or “ticket sizes”. Both issues can potentially be addressed by aggregating projects into diversified portfolios; an approach commonly used by investors in several contexts, but little investigated in the context of rural electrification [94].

Individually, microgrids are too small for typical financial investors to consider, and in order to conduct due diligence, and to reduce risk in order to get a reasonable return on investment, there is a need to aggregate multiple microgrids in a portfolio [95]. Investors tend to prioritise countries where a clear electrification programme and transparent and amicable regulatory framework exist, ideally with geographical areas mapped for microgrids demarcated from grid extension and SHS to reduce grid arrival risk [56].

Business approaches to rural electrification efforts in the Global South are hampered by serving customers living in poverty with a low ability to pay. Microgrid businesses in SSA are no exception and similarly recognised as challenging; in most markets due to the cost per connection and low average revenue per customer, a subsidy is needed with donor programmes aligned with microgrid developer’s needs. This thesis aims to address these challenges by providing a structured approach to assessing microgrid business feasibility, and in doing so providing investors and donors a transparent and structured approach to design assumptions and predicted financial performance, allowing for more informed and ultimately lower risk decisions on financing and investment.

2.2.8 Environmental considerations for solar microgrids

Decisions on microgrid implementation must be informed by environmental, health and safety (EHS) risks. It is necessary to understand EHS risks and incorporate measures to monitor them and mitigate negative impact [96]. Microgrids have three kinds of potential EHS impacts: direct, indirect and cumulative, outlined in Table 4.

Table 4 Environmental Health and Safety Impacts of Mini-Grids [96]

	Direct Impacts	**Indirect Impacts**	**Cumulative Impacts**
Renewable Energy Mini-grids	• Land use and land use change • Localized air, water and soil pollution • Battery waste pollution • Water diversion or impoundment • Health and safety impacts on workers and communities	• Material production • End-user industry • Equity of access	• Waste production • Greenhouse Gas Emission of supply chain activities • Population effects on threatened biodiversity
Additional impacts for mini-grids using Diesel Generators	• Air pollution • Noise pollution	• Fuel source production	• Fuel sourcing • Greenhouse Gas Emission of power generation

From an environmental perspective, microgrids powered by renewable energy are considered a climate-neutral technology with lower environmental impacts than traditional systems due to their utilisation of solar resources [97]. However, end-of-life management of microgrids still poses a significant challenge to their environmental sustainability, as the production and disposal of relevant equipment from cables to switchboards to solar modules has an ecological footprint [98]. Microgrid equipment may fail, in many cases due to a lack of proper maintenance, and is often improperly disposed, risking adverse health effects for people and the emission of environmentally harmful substances. Proper end-of-life management is therefore a key component of sustainable microgrid solutions, especially regarding the correct disposal of batteries [68] [99], [100]

Life cycle assessments for solar microgrids have been completed revealing that when normalized per kWh of electricity consumed, PV microgrids, particularly PV–battery systems, have lower impacts than other energy access solutions in climate change contributions, particulate matter, photochemical oxidants, and terrestrial acidification When compared to small-scale diesel generators, PV–battery systems save 94–99% in the above categories [101]. A brief life cycle environmental impact assessment for the pilot microgrid used for the data analysis in this thesis has been conducted [102], however the focus of this thesis is on social and financial themes and investigation of environmental impacts including conducting a full and detailed life cycle assessment was deemed out of scope for this thesis.

2.3 Social enterprises

Market-based solar products and services are widely accepted as being vital to addressing energy poverty in the Global South [43], and solar microgrids hold potential to address SDG 7 by enhancing socio-economic wellbeing through improved quality of life, access to public services, job creation and entrepreneurship opportunities and industrialisation enabled by access to energy [64]. However, the preceding section has shown that accelerating solar microgrid deployment demands more than technical research; effective energy planning methodologies and delivery models are needed for rapid and sustainable microgrid implementation.

The concept of the ‘energy delivery model’ describes a core set of activities and actors that constitute an energy service required to make energy infrastructure sustainable [19]. It highlights the importance of understanding how to fulfil end-users’ needs and the supporting services required to make the energy infrastructure sustainable. The concept emphasises the importance of wider enabling-environment policies, additional supporting services and socio-cultural factors when designing and delivering energy services for low-income communities. Traditionally, energy service delivery models have followed frameworks based on public, private, charity or hybrid models with varying degrees of success. The efficacy and sustainability of these approaches to reduce poverty through energy provision varies between models and has been questioned by stakeholders [103], [104], [105] [106].

Broadly defined as the use of market-based approaches to address social issues, a social enterprise provides a “business” source of revenue for civil society organizations [107]. Recognising the need for innovative alternatives to status quo delivery models, social enterprises have begun to fill in the gap between public and private provision of electricity to address energy poverty. This section outlines definitions for social enterprises, and proposes defining characteristics for a solar microgrid social enterprise based on existing literature to build a framework of understanding for the analysis provided in the thesis.

2.3.1 Social enterprise definitions

‘Social enterprise’ is a collective term for a range of organisations that trade for a social purpose [108]. Several definitions for a social enterprise exist, including:

- “a business with primarily social objectives whose surpluses are principally reinvested for that purpose in the business or in the community, rather than being driven by the need to maximise profits for shareholders and owners [109]”; and
- “organisations who are independent of the state and provide services, goods and trade for a social purpose and are non-profit-distributing [110]”.

Social enterprises exist within the third sector of the economy, aiming to address perceived shortcomings in market or governmental provision of social welfare, and have been acknowledged as a potential driver of social progress [111]. The autonomous nature of the social-economic model applied by such organisations can represent a viable means to reduce state social welfare dependence, and is a proven model for social change [112]. Clear potential exists for social enterprise models to create both social and economic value, while further having an ability to address social and ecological challenges caused by neo-liberal market economies [113]. The innovative business framework is therefore a potential enabler for sustainable development by balancing the three sustainability pillars in social, economic and ecological domains[114].

Scholarly interest in social enterprise has progressed beyond early focus on definitions and context to investigate management and performance. However, to date, social enterprises have yet to be explored as serious instruments of sustainability transitions [112], and little research has been conducted that systematically interrogates the dynamics of the sector, its discourses, representations and practices [113]. Within the energy for development sector, delivery model innovation with a social focus has become a key means of embedding energy justice concepts in business models for energy provision [104]. Addressing these gaps, this thesis seeks to advance academic discourse on the alignment between social enterprise and energy delivery models specifically regarding solar microgrids.

2.3.2 Defining characteristics of a Solar Microgrid Social Enterprise (SMSE)

The purpose of this section is to propose and justify a set of key characteristics for an organisation offering solar microgrids through a social enterprise delivery model such that it supports the achievement of SDG7. The argument presented is based on social enterprise characteristics defined by existing literature [21] [109] [22], [107], [112], [115], adapted and contextualised to consider how SMSEs should define their purpose and strategy.

2.3.2.1 Social purpose

By definition, the primary purpose of a social enterprise is to provide social impact, with commercial activity the means to achieving this. SMSEs should therefore have primary objectives that speak to the social development priorities of the local communities they intend to serve. To enable quantification and tracking of their impact, it is proposed that SMSEs align their social mission within the framework of the SDGs, using methods such as proposed by [116]. In practical terms, SMSE should therefore strive to connect all members of a community that want it, rather than only those that can afford the electricity service.

Most social enterprises will have more than one objective, with many having goals primarily environmental [117] [118] [119]. Social and environmental challenges are two sides of the same coin, and it is imperative that to maintain a SDG contribution, SMSE have environmental objectives in their governing documents. Additional to a clear goal of utilising low carbon solar energy in comparison to fossil fuel competitors, SMSEs can go further to monitor, evaluate and reduce their environmental impact. This can be achieved by auditing project carbon emissions (especially from transport), investing in system lifecycle analysis research, and disposing of components such as batteries in a responsible manner.

2.3.2.2 Trade engagement in the marketplace

The primary revenue source of social enterprises is commercial, relying on market activity from selling goods or services to operate and to scale-up their operations [120]. Many microgrids are examples of one or more organizations that seek to generate revenues by providing a service (electricity) that helps reduce poverty [90]. Other sources of income can include contracts, including service level agreements, usually with the public (or-quasi-public) sector to deliver services [21].

However, due to current legal frameworks and associated lack of feedback on an appropriate and socially accepted tariff structure, microgrid revenue streams are usually quite low and can be insufficient to cover maintenance costs, at least in early stages [121]. Grants and subsidies for initial capital costs can therefore be a key enabler for the successful development of pilot or early stage minigrids [122]. Given the nascent market for microgrids, it is likely the majority of income will come from these donor sources in the short term.

Grant funding can restrict freedom of operations, can foster dependency syndrome [123] and is arguably unsustainable for long-term viability of energy enterprises. SMSEs should therefore accept donor funds for capital or operational costs to pilot microgrids in early stage development, but design a strategy for long-term financial independence through the sale of products and services. Primarily this will be electricity sales, but additional services may include appliance financing, Productive Use of Energy service offerings, or offering consultancy and technical support to other SMSEs.

2.3.2.3 Reinvestment of profit

Social enterprises target economic sustainability with a wider social mission, reinvesting profits generated to achieve multiple bottom lines [124]. Reinvesting profits ensures operations do not increase personal wealth of those involved and external owners of capital cannot exert control because of their shareholding. Mechanisms can be established to reward workers or customers for efforts in achieving commercial survival and success, however these should not be related to any capital contribution [21].

These restrictions must be clearly defined and adhered to in a SMSE business plan. The business strategy should define a maximum amount of profit which may be used for workforce bonuses and customer benefits, and a minimum amount which should be paid for community benefit. SMSE assets, including accumulated wealth should be held in trust to benefit communities living in energy poverty. Besides the discussion on grants listed above, any capital used by SMSE social enterprise has to be paid for, with debt finance required to be paid with interest as well as regular capital payments, and equity agreements involving deferred payment relating to performance [21].

2.3.2.4 Community engagement and participation

An emerging trend for communities to take greater responsibility for their own socioeconomic development is evident, and social ventures with a focus on community engagement have the potential to deliver benefits over and above economic outcomes as they closely engage with people with a shared interest in the creation and management of these ventures [108]. Accordingly, participation and empowerment are often forwarded as legitimizing factors for social enterprise [124].

Importantly, for energy focused social enterprises, local people are involved in active dialogue on the future of the energy system for their community, fostering agency, ownership and engagement [125]. New approaches conceptualizing the form of governance for such organisations is essential, centred on ownership, participation and community control [82]; and innovative business models that combine social and community-based approaches with entrepreneurship are demonstrating improved sustainability [126] [127] [128].

With such a clear impetus for community engagement and participation in both social enterprises and microgrids more widely, a key aspect of a SMSE strategy should be to recognise the importance of trust, accountability and effective networks in a community, and to invest in developing strong relationships with customers and communities served by the microgrid. Primary goals should be to establish clear communication channels between the SMSE and the community, with mechanisms for bi-directional dialogue to inform change and improve impact and sustainability of the organisation. Options for achieving this include initiating Village Energy Committees, allowing community representatives to engage in democratic processes within the organisation, or exploring options where every customer is a member of the SMSE.

2.3.2.5 Organisational accountability

Accountability in this sense means accounting openly to stakeholders for what the organisation does, primarily to its constituency, or those people whom it affects. Practising accountability requires effective methods of gathering relevant information, consulting stakeholders, reporting on impacts and discussing strategy implications. It also requires the establishment of channels of accountability, the various way through which an organisation engages with its stakeholders and reports on its performance [21].

For an SMSE, accountability should involve transparency on the organisational adherence to the above characteristics, with stakeholders to be accountable to including donors, government institutions and other players in the private sector, while the constituency is the rural communities served by the microgrid. SMSEs should therefore invest in clear communication to the communities they serve and the network of organisations within which they operate, and participatory processes for decision making. Suggested measures include customer contracts outlining clear roles and responsibilities, appointing key community representatives to serve as conduits between community and SMSE, and holding community meetings to discuss significant changes to service delivery. Specific attention and resources should be assigned to monitoring, evaluating, and reporting on the social impacts of the organisation, discussed more in Section 4.3.

2.4 Measuring and understanding social impact of microgrids

Having established that the *raison d'etre* of social enterprises to produce positive social impact within the communities they serve, an understanding must be gained in how to quantify the social impact of SMSE in order to assess whether they achieve their primary goal. Accordingly, this section maps the landscape of academic and industry literature relating to the current understanding of social impact caused by rural electrification and mini or microgrids, and forms a foundation upon which the social impact methodology research conducted in this thesis has been built. The literature review comprises three sections: key academic papers explaining the social value of electrification, a discussion of current methodologies used to evaluate mini and microgrid electrification, and selected practitioner reports with recent minigrid evaluations from the field. Relevant search terms including "*mini-grids, social impact,* and *evaluation methodologies*" were utilised in search engines, prioritising results focused on SSA.

2.4.1 Social value of electrification for development

Electricity can improve quality of life by increasing the level of health, education, welfare, and technology [129]. Rural electrification in particular, defined as the percentage of the rural population with access to electricity, has been found to be a crucial part of socio-economic development [130]; and responsible for increasing youth literacy rates and improvement in health care through upgraded facilities [131] [132]. It has also been found to enhance employment, especially among women [133], by enabling income generating activities, and advancing rural productivity [134]. On a national scale, per capita electricity service is highly correlated with improvements to the Human Development Index, showing extremely strong marginal diminishing benefits [135].

In their short communication regarding the social value of mid-scale energy in Africa, Miller et al. define the social value of energy "*in terms of the total value derived by an individual or community from the use of energy, including economic and other forms of value, less any risks or burdens that accompany energy production, transmission, and consumption*" [136]. They suggest a need to consider social value of energy alongside cost comparisons in designing projects to reduce energy poverty. They state that mid-level energy initiatives (such as microgrids) have potential for higher levels of impact, but social value considerations are frequently omitted with a tendency to exclusively focus on electricity supply. Assessing the social value of electrification ensures that community energy systems create a positive feedback loop enabling growth and delivering value by avoiding system disrepair and disuse.

[137] confirms this view of combining a technical outlook with a sociological one during system design in their study of how technology integration affects remote communities. Their argument is based on the idea that social factors are often key in explaining system failures (alongside technical causes of system failures). Understanding social factors and their role played in system failures improves prospects of future prevention. They propose that technology adoption cannot be considered successful until verifiable evidence of perceived benefits are actually delivered to recipient communities. The paper concludes by suggesting that exploring social habits, cultural attitudes, and the networks of social relationships and behaviours clears the path for a more precise explanation of unsuccessful design and adoption of electrification technologies. This, in turn, translates into a socio-technical solution that is more likely to result in the success of such programmes.

[138] identified competing approaches to renewable energy system deployment: some are socially orientated, while others have a commercial objective "*to create a market for electricity services*". The different approaches to the engagement in rural electrification reflect different levels of ambition and expectation, and it is most certainly easier to evaluate a project with a main objective to "*create a market*", as opposed to a project with a social dimension intended to serve as a "*prerequisite for poverty reduction*".

2.4.2 Monitoring social impacts of microgrids: methods, frameworks and results

Despite a large number of rural electrification projects being implemented in developing countries, there are few published in-depth evaluations of the effects of these projects on sustainable development [138]. Technological performance monitoring frameworks for mini-grids exist [139], but rarely involve a comprehensive methodology that considers the full range of potential impacts; with societal impact factors being a notable omission from most.

Practical Action's Poor People's Energy Outlook (PPEO) [140] outlines a framework for observing and evaluating the social value of energy projects at a local level through an ecosystem approach that encompasses the SE4All Global Tracking Framework [141]. This is achieved by specifying the community energy services as well as recording the existing social and entrepreneurial activities; recognising the externality impacts of certain energy uses that are detrimental to the community; and identifying the essential nature of key influencing parameters such as social capacity, policy and financing frameworks. Essentially, the PPEO recognises the need for socio-technical design, refuting the common dogma that techno-economic challenges such as increasing system energy output and customer consumption while reducing costs through efficient design are separated from social aspects of capacity building, policy and regulatory assessment and advocacy and low income tariff structures.

[138] presents a method for the evaluation of rural electrification projects that covers five dimensions of sustainability: technical, economic, social/ethical, environmental, and institutional. The methodology uses indicators to help create a better understanding of how a specific project contributes to sustainable development. [142] utilised this framework to measure the sustainability of mini-grids in Peru and Nepal. Fieldwork was conducted in three case study sites using a variety of evaluative methods, including semi-structured interviews with users and managers, transect walks, photographic evidence, and observations. Villagers' perspectives were triangulated against the results of semi-structured interviews held with the implementing agencies, enabling different levels of analysis to be embedded in each case study. A series of 43 sustainability indicators were developed for evaluating the grids; categorised into the five themes of sustainability indicators presented in [138]. As well as evaluating welfare benefits, foundations were identified to ensure such benefits could take place: community mobilisation, productive uses, and a supportive enabling environment. The enabling environment included access to financing, technical support and supply parts, and establishing favourable institutional, technical and regulatory frameworks.

[134] conducted a detailed case study analysis of a microgrid in rural Kenya to quantify the effect on social and business services in the village. They recorded a 20-70% growth in the income levels of local workers in small and micro enterprises, resulting from a 100-200% increase in productivity per worker from using electric equipment. Additionally, access to electricity improved the social and business services provided by the village infrastructure such as schools, markets, and water pumps, as well as boosting agricultural productivity. Teachers and parents interviewed all agreed that academic performance had measurably improved, although no quantitative figures are presented. Financial savings were also made in switching from kerosene to electric lighting, with additional benefits identified through ICT use and offering vocational courses, impacting examination scores and employability, and increase in teacher retention with access to lighting and television for the staff. In general, increased productivity and growth in revenues was found to achieve significant social and economic benefits for rural communities.

[143] investigates if the provision of electricity through solar mini-grids could contribute to improving business performance in rural Kenya, using a difference-in-differences approach to compare business outcomes before and after electrification in regions with and without mini-grids. Their results show that nearly two years after the implementation of mini-grids, these have not had the intended effect of improving business performance, electricity consumption has remained low and demand for the products and services sold by local businesses has not picked up after the arrival of mini-grids. They

recommend adjusting the size of the systems to the actual demand and implementing complementary measures to improve agricultural productivity and access to external markets. An alternative view would be to stimulate demand through community engagement on productive uses of energy and business development, encouraging more connections and more businesses.

2.4.3 Practitioner experiences of measuring social, economic and technical impact of mini-grids

An evaluation of 20 mini-grids in Africa and Asia [25], considered a number of parameters including service level, number of connections, demand per connection, type, capacity and capital cost of technology. Financial parameters included sponsor type, payment method and mechanism, tariff, business model, profitability, financing, payback and perceived risk. Financial insights include mini-grid payback of the mini-grids varying between 1 and 12 years, with an average of 6.2 years. The mini-grids surveyed had an average per capita demand of 2.5–30 kWh/month. The key (and only) social impact statistic provided in this report is that two of the nine Distributed Energy Service Companies had a 23% disconnection rate after 5 months and a 10% disconnection rate after 50 months, while the other seven had no disconnections. The report does not given any reasons for these disconnection rates, or why the others had no disconnection rates. The report illustrates the satisfactory service provision and affordability of these systems, but does not provide any information on how positive the impact on the local communities was, or how it could be improved.

Early insights into solar PV mini-grid operations in rural Kenya are described in [144] providing a wealth of information on social impact. Generally, demand for mini-grid electricity in Kenya is strong and growing, and surveyed consumers cited economic growth, increased security and health benefits as primary drivers for this demand growth. Although most consumers had a low consumption of <250 Wh/day, through a pre-pay model, the majority of customers kept their accounts constantly in credit. Mini-grid consumers shifted almost entirely away from fossil fuels, with kerosene and disposable battery use decreasing from 86% to 4% and diesel generator use reducing from 10% to 0%. Pre-installation survey estimates of energy use compared with actual consumption revealed an average of 15% overestimation of anticipated demand. Customers with greater disparity between expected and actual consumption were in general less satisfied

The Rockefeller Foundation [145] conducted an evaluation of the impact of rural electrification in Uttar Pradesh and Bihar, India. The Foundation utilised a model that provides electricity through mini-grids for lighting and business use. The study found that 80% of the overall customer base were of low-medium economic status, while 90% of domestic customers were in low wealth groups. The theme of productive use was strongly emphasised, and although 80% were residential customers, micro-enterprises in general have benefitted from the mini-grid with 60% of owners reporting improved lighting conditions, increased appliance ownership and ease in business operations.

2.5 Identifying the literature gap fulfilled by this thesis

The nascent nature of the microgrid sector in SSA has resulted in an emerging academic literature that lacks maturity with some gaps evident. This section outlines the status quo in terms of academic research on mini and micro-grids, as well as planning tools available to microgrid practitioners. The purpose of this section is to locate the contributions of this thesis within the landscape of academic and industry literature on microgrid business planning theory.

2.5.1 Existing academic and industry research on planning tools and methodologies for assessing microgrid feasibility

Several academic-industry relationships exist between mini and microgrid developers and researchers, offering a unique opportunity for researchers to obtain primary data to inform their studies, while mini-grid developers receive expert analysis to inform their operations, often being too resource constrained to effectively carry out. The most relevant of these relationships, focused in SSA are highlighted here to indicate the research being conducted and how this thesis, and the relationship between University of Strathclyde and United Purpose Malawi, upon which this thesis is based on, fits. The relationships highlighted below demonstrates that mini and microgrids are an emerging field of interest growing with several funded research streams coming online in the last few years. The focus of the majority is technical and financial research, looking at business models to scale. This validates the thesis topic as a necessary topic to inform global microgrid efforts, but also demonstrates the lack of research linking socio-techno-economic themes as well as a paucity of research activity directly related to Malawi.

2.5.1.1 Crossboundary Mini-grid Innovation Lab, USA [146]

Crossboundary claim to be Africa’s first research and development fund exclusively focused on testing new business model innovations for mini-grids, and improving the ability of minigrids to provide African businesses and households with electricity. Their research themes include appliance financing, bulk procurement, grid competition, offering internet services, testing smart meters, exploring modular grids, predicting consumption and tariff reduction.

2.5.1.2 Carnegie Melon University (CMU), USA [147]

CMU run a Mini-Grid Innovation Lab for Africa which aims to sustainably deploy electrical mini-grids in rural Africa. The lab iterates innovative solutions for the application of mini-grid technology by analysing business models, prototyping efficient appliances, and refining solutions for its customers.

Their work supports mini-grid developers and gathers evidence for the mini-grid's need, with links in Rwanda and add to the knowledge base of East Africa.

2.5.1.3 University of Southampton, UK [148]

The Energy4Development programme at Southampton has to date installed six community managed solar photovoltaic (PV) mini-grid systems in Kenya, Uganda and Cameroon with more in planning. The research and development programme has been extended to study and explore the operation and resilience of local mini-grid networks, including their appropriate transition to the national grid connectivity. Their research include consumption profiles, optimisation and cost of energy at different community applied tariffs.

2.5.1.4 Energy4Impact (E4I) [149]

E4I provide financial and technical assistance to support a range of innovative projects, initiatives and business models in a number of ways, including realise their ideas, developing their management and business skills, and providing access to resources or facilities required to grow their businesses. In an effort to stimulate electricity demand and increase affordability, E4I is piloting a tariff-by down facility to enable consumers to afford and utilise more power; and a working capital facility for mini-grid developers to finance the purchase of energy efficient appliances to be sold on credit to their consumers (households and commercial). The intention is to produce an evidence base that supports the case for more systematic support for mini-grids and the low-income customers and businesses they serve on the key business model drivers: tariff and consumption. Their research is focused on informing practitioners in Africa through mini-grid business model designs.

2.5.1.5 Green mini-grid market development programme [93]

The Green Mini-grid Market Development Program (GMG MDP) supports the scale-up of investments in commercially viable Green mini-Grids (GMG) projects through a broad range of interventions to improve the enabling environment, including market intelligence, business development support, policy and regulatory support, access to finance, and quality assurance. Financed by the African Development Bank, the programme is supporting developers on issues ranging from business planning, market development and grid design to project finance, grid operation and maintenance. The main objectives are to accelerate the development cycle of Green Mini-Grid projects and to improve their bankability, create links between market actors in order to address gaps and developer capacities, technology, financing, and contribute to the evidence base of commercially viable projects.

2.5.1.6 Malawi Specific mini-grid research

In Malawi, where the case study for this thesis is based, the majority of off-grid energy research to date has mostly focuses on Solar Home Systems or stand-alone systems, with many specifically looking at sustainability [150]–[152]. Policy related research has looked at District Energy Officers and decentralization [153], [154], while PESTLE analysis has been conducted on the energy access ecosystem [155] and social science-based research focusing on energy justice issues [156]. Emerging microgrid research utilising primary data is limited due to the lack of mini and microgrids installed in country, and most are policy or technical briefs rather than academic papers [17]. Chapter 4 includes an in-depth overview of Malawi's energy situation referenced with these outputs.

The Malawi Integrated Energy Planning Tool (MIEPT) is a decision-support tool designed to help decision-makers in Malawi to develop an integrated energy plan for the country incorporating requirements for universal residential and institutional electrification, access to clean cooking, healthcare facility electrification, and vaccination rollout modelling. It was developed in collaboration between the Malawi Ministry of Energy and SE4All and was released in 2022 [157]. To identify pathways and opportunities for expanding energy access, the analysis considers a suite of supply-side solutions, including the grid, mini-grids, solar home systems (SHS), as well as a variety of demand-side factors, such as affordability. MIEPT is comprised of three main components: an energy supply model, an energy demand model, and a cost-benefit analysis tool. MIEPT has been used to inform decisions on energy sector investments and is seen as an important tool for promoting sustainable energy development in Malawi. The MIEP offers a similar geospatial least cost approach to energy planning as described in the market assessment methodology of this thesis, and offers more in depth analysis and more accurate assumptions for grid and SHS competitor technologies, however doesn't include solar resource or maintenance costs when modelling microgrids, which this methodology does.

2.5.2 Peer reviewed literature on microgrid business model methodologies

This section outlines key academic literature regarding microgrid business methodologies and identifies where this thesis builds on and contributes to the status quo of knowledge and understanding is modelling and strategy development for solar microgrids.

Santos et Al [158] propose a framework design for microgrid optimisation using technical, social, and economic analysis using a small island case study. It provides a multi-objective optimization framework with different criteria considerations, such as the inhabitants' cost of living and inter-cultural aspects, instead of traditional technical and economic analysis. The results show the applicability of the proposed framework showing better alternatives when compared with actual or future improvements in the study case scenario. Although providing a welcome addition of social factors in addition to technical and economic, it doesn't offer opportunities for modelling at scale, and doesn't link in market assessment methodologies.

Kajongwe’s [159] research was motivated by Zimbabwe's slow adoption of mini-grids, specifically the lack of SMEs utilising productive use of energy in the sector and the associated negative contribution to the country's goal of achieving universal access to clean and sustainable energy by 2030. The study conducts a literature review on learning from other countries' experiences with SME and mini-grids and discovered that in order to accelerate the adoption of renewable energy mini-grids by SMEs in Zimbabwe's manufacturing sector, effective policy is required to allow for the pooling of resources and risks from a number of SMEs. This, they argue, will increase their capital base and their chances of obtaining loans from local banks and climate funds. As a result, the study recommends that Zimbabwe implement policies and regulations that encourage SMEs to use renewable energy minigrids for workplace electricity access. PUE has been identified as a critical component of ensuring an SMSE's financial sustainability and social impact, and the research is also centred on Africa; however, it focuses on only one aspect of the SMSE ecosystem and does not present a methodology-based research that can be replicated in other regions.

Ighravwe [160] presents a methodological framework for ranking mini-grid business models, utilising multi-criteria multi-decision (MCMD) making tools. The framework combines Criteria Importance Through Inter-criteria Correlation (CRITIC), TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) and WASPAS (weighted aggregated sum product assessment) methods. The applicability of the proposed framework was tested using four potential mini-grid (private, government, community-based and public-private) business models in Nigeria, ranked using twelve criteria. They found that electricity tariff and energy demand were the least and the most important criteria, respectively, for selecting a mini-grid business model. The study suggests that mini-grid business models in developing countries should be either private or community-based business models. The use of MCDM tools is touched upon in the market assessment methodology of this thesis, and such techniques can provide valuable logic-based tools to aid decision making. Ighravwe uses quantitative analysis allowing value to be assigned to financial modelling and offers more direct and valuable outputs for a policy maker, investor, or solar microgrid practitioner.

Gambino’s study [161] addressed a need to standardise effective methodologies and procedures to develop off-grid/mini-grid systems in order to successfully deploy decentralized energy systems in developing countries at scale. The study recognises that energy need assessment provides inputs and assumptions used in business modelling and mini-grid design, and the accuracy of its results directly affects the technical and financial feasibility studies. The research developed a methodology for energy needs assessment of rural communities to obtain reliable input data for optimised mini-grid development, in order to reduce both financial and economic challenges by mitigating uncertainties in electricity demand and system sizing. Taking into consideration that target communities differ in terms of needs and context conditions, the paper describes an inclusive methodology that can be adapted case-by-case, and gives priority to data collection methods able to achieve a large sample representative of the market, while also estimating energy consumptions from electricity substitutes. The research has similar objectives to this thesis in terms of progressing methodologies for large scale decentralised renewable energy infrastructure, but covers a wider scope in terms of off-grid system more generally, and wouldn't offer the same utility to a decision maker interested specifically in solar microgrid social enterprises. The methodology used in this paper offers novelty by emphasizing the importance of carrying out data collection activity with a focus not only on statistical results but also gathering opinions and suggestions from population, local authorities and stakeholders in order to promote a bottom-up approach and lay the groundwork for a participatory project development, positing that community engagement strategies can maximize sustainability and transformative potential of mini grids. This bottom up, community engagement and participatory approach is built on through the social enterprise theme of this thesis.

Williams' thesis [162] focused on solar diesel microgrids for electricity access in East Africa. The research identified and quantified primary sources of investment risk in microgrid utilities and investigated ways in which these risks can be mitigated to make microgrid businesses more viable. The risks identified include fuel prices, foreign exchange rates, price elasticity of demand, and the level of demand for electricity. The research found that there is a lack of quantitative analysis to critically evaluate the key drivers of risk in microgrid utilities, or how different business models and technologies affect the potential for these projects to attract finance and scale up deployment. The study introduces the Stochastic Techno-Economic Microgrid Model (STEMM), which enables assessment of the effect of technical design decisions as well as financial conditions on the financial viability of microgrid projects from an investment perspective, testing it on case studies in Rwanda. The findings indicate that major contributors to risk are fuel price volatility, uncertain electricity demand, and foreign exchange risk for investments in hard currency; and that choice of technology strongly influences the risk profile of microgrids, with solar powered microgrids susceptible to demand uncertainty and diesel-based systems exposed to fuel price volatility. The study also developed predictive models of electricity consumption for individual customers working with minigrid provider PowerGen in Tanzania. By comparing customer demographic data collected prior to connection to measured load profiles in existing minigrids, estimates of load profiles for new minigrids could be made on demographic data. The research parallels this thesis with an impetus to reducing risk for microgrid investors, and is also purely focused on microgrids rather than minigrids. The research is similar to others in its focus on techno-economic themes, and doesn't offer insight on social aspects or market assessment considerations of solar microgrids.

Table 5: Summary of key academic papers analysed for the literature review, a critical appraisal of each and how this thesis builds on the research published

Paper	Merits and relevance to this thesis	Limitations	How this thesis builds on the research
Santos, et al. Framework for microgrid design using social, economic, and technical analysis	Holistic analysis of microgrids incorporating technical, social, and economic analysis. Comprehensive steps outlined to inform whether a particular design is feasible, and if not why.	Not specifically solar microgrids and includes other generation types (e.g. wind turbines). Only one microgrid modelled, doesn't allow for multiple sites or business modelling at scale. Lacks detailed financial planning.	The process framework incorporating iterative calculations and decisions is built upon, widening the framework for a single site to include a market assessment and multiple sites, with more functionality and detailed financial planning.
Kajongwe et al. Assessment of the Feasibility of Deployment of Renewable Energy Mini-grids for Rural Electrification for SMEs in Zimbabwe	Contributes to a knowledge base for microgrids in Africa, specifically in terms of economic impact, ownership/management models, and productive uses of energy. Builds an evidence base for policy makers to increase deployment of microgrids	Key focus is how microgrids impact performance and sustainability of SMEs, rather than looking microgrid developer/operator feasibility. Just a literature review, no primary data analysis. Geographic limitation to Zimbabwe, although case studies used from wider Africa	The importance of PUE in both improving microgrid business models through stimulating demand, and providing economic impact in rural communities is taken forwards as a key theme in this thesis, applying a more robust quantitative methodology utilising primary data to assess microgrid feasibility.
Ighravwe et al. Selection of a mini-grid business model for developing countries using CRITIC-TOPSIS with interval type-2 fuzzy sets	Identifies criteria influencing the choice of mini-grid business and ownership model. Emphasises the importance of business models for microgrid sustainability, and uses a logical approach to investigate	Informs on a high level of which business model approach to use, doesn't look into detail the feasibility of each by applying primary data or conducting financial modelling. Case study limited in geographical scope to Nigeria	The study suggests that mini-grid business models in developing countries should be either private or community-based business models. This thesis proposes a social enterprise business model which combines elements of both models, Ighravwe's research adds validation to this approach.
Gambino *et al.* Methodology for the Energy Need Assessment to Effectively Design and Deploy Mini-Grids for Rural Electrification	Detailed methodology for quantitative approach to energy needs assessment, which is essential for informing technical design, tariffs and revenues. States the need for both qualitative and quantitative data to inform design decisions.	Scope is wide in terms of off-grid system more generally, and wouldn't offer the same utility to a decision maker interested specifically in solar microgrid social enterprises. Only covers one input parameter (demand), doesn't consider component costs or financial modelling.	Demand is an essential element for informing technical and business design, and the primary data analysis methods are taken forward in this thesis. Bottom up, community engagement and participatory approach is encouraged, and this approach is built on through the social enterprise theme of this thesis
Williams, Microgrid Utilities for Rural Electrification in East Africa: Challenges and Opportunities	Robust methodology for identifying risk in solar microgrids, utilising techno-economic modelling and quantitative analysis. Specifically looking at solar microgrids. Validates that a set of tools that needed to assist microgrid developers and investors make more informed design and investment decisions.	Looking at risk from an investment, the model assumes a purely private sector approach, and doesn't take into consideration the social impact or community engagement. Primary outputs are financial indicators regarding the investment attractiveness of the microgrid, the model doesn't look into detail on operations or detailed business design	This thesis builds on Williams' approach to prove quantitative analysis to inform microgrid and technical design to attract finance and scale up deployment. The financial modelling uses similar input parameters but a different industry based approach (Odyssey). The addition of a KPI framework to track performance and impact provides additional insight to refine and improve microgrid business performance.

It has been shown that several methodologies to support decision making on mini and microgrid business model exist, although none could be found framed specifically as a SMSE, with the examples given above focusing on techno-economic aspects of business modelling, and often just taking on one aspect of the business plan in detail. The addition of social impact measurement and market assessments, and modelling solar microgrids at scale, all offer novel contributions to the existing status quo. In addition, no published research could be found on microgrid business models in Malawi, highlighting the significant novel contribution offered through this thesis in primary data and analysis.

2.5.3 Microgrid design and business planning tools

Much of the state of the art of microgrid design planning tools comprise utility-scale tools adapted to the needs of mini and microgrids, although some applications exist that have been developed specifically for the mini and microgrid markets [41]. Several industry standard planning tools have been developed and are available for practitioners, mostly focused on technical design or business model planning. They also normally focus on a single element of microgrid design or implementation, and rarely have a holistic approach. This section provides a summary of mini and microgrid planning tools currently available to practitioners, outlining key features as well as limitations to their use based on a summary of mini-grid tools compiled by [163]. Where applicable, gaps or shortcomings addressed by this thesis are highlighted.

2.5.3.1 Microgrid technical and system design tools

HOMERPro [164] is an industry standard software offering techno-economic modelling for simulation, optimization, and sensitivity analysis of microgrids, used and discussed in more detail in the methodology presented in Section 3. Some other commercial design tools have been developed by equipment manufacturers such as the SMA off-grid calculator [165] which allows for dimensioning of off-grid systems, dimensioning PV and system simulation. Others allow for detailed technical analysis like Nsol [166], specifically for PV-generator hybrids giving operating costs and system behaviour, or Paladin [167] which provides more generic comprehensive power systems simulation platform for modelling, analysing and optimizing power system performance. ETAP [168], is another generic electrical analysis software that spans from modelling to operation, and PVSyst [169] is a software package that calculates energy yields for a given site considering solar irradiation and temperature through its meteo database. Although these tools can assist in technical design of off-grid PV systems, they do not cater explicitly for mini or microgrids.

GIZ’s mini-grid Builder [170] is a publicly available tool allowing users to enter data from site surveys into a database and perform calculations on the energy demand, and the required generation capacity, as well as including financial aspects to calculate an initial project budget. It doesn’t provide the detailed analysis this methodology is proposing, or include social impact or market assessment functionality.

Demand Analyst® [171] is a tool for planning rural electrification, allowing estimation of the evolution of electricity demand in each study locality throughout a planning period to optimize equipment necessary for the electrification of a village or group of villages in a given area. Unlike traditional "top-down" approaches of demand forecasting, Demand Analyst® is based on a detailed analysis of the demand for each end user, including different classes of including households, public services, commercial and others established from socio-economic surveys. This tool could be included in further development of the methodology proposed in this thesis to refine understanding of demand growth.

2.5.3.2 Microgrid financial planning and business model tools

Several generic tools exist to assist in business planning and development, but don't specifically speak to mini or microgrid developers. For example, the business model canvas tool [172] allows users to capture an entire business model in one place, helping to invent new models and improve old ones by allowing entrepreneurs to sketch out and test the viability of their business model quickly. The tool has sections including value proposition, key activities resources and partners, as well as cost and revenue structure, outlined in Figure 13. Although it allows high level business structure planning to be conducted quickly to help understand and plan the business elements of a microgrids, it is not specifically designed for microgrids and more detailed business planning will be required.

<table>
<tr><td rowspan="2">Key Partners</td><td>Key Activities</td><td rowspan="2" colspan="2">Value Proposition</td><td>Customer Relationships</td><td rowspan="2">Customer Segments</td></tr>
<tr><td>Key Resources</td><td>Channels</td></tr>
<tr><td colspan="3">Cost Structure</td><td colspan="3">Revenue Structure</td></tr>
</table>

Figure 13 Business Canvas Tool

Other tools provide specific guidance on renewable energy budgeting and financial planning, but not specifically microgrids. RETScreen [173] is a Clean Energy Management Software system for energy efficiency, renewable energy and cogeneration project feasibility analysis as well as ongoing energy performance analysis. It does not include a chronological simulation which is critical for microgrids. The Cost of Renewable Energy Spreadsheet Tool (CREST) [174] is an economic cash flow model designed to allow policymakers, regulators, and the renewable energy community to assess project economics, design cost-based incentives (e.g., feed-in tariffs), and evaluate the impact of various state and federal support structures. The IRENA Project Navigator [175] enables project developers to create their own workspace where they can start their own renewable energy project and navigate through each of the development phases of their project. Both these tools follow similar methods to the financial modelling used in this thesis, but don't cater specifically for SMSEs.

Several tools have been developed to design mini and microgrid tariffs, using various methods. The Power and Tariff Calculation Tool for Solar Mini-grids in Indonesia [176] allows users to estimate solar mini-grid capacity and investment as well as electricity fee, with electricity tariffs calculated based on common practices in rural electrification where the mini-grid is managed by the community. The minigrid financial modelling tool [78] supports the calculation of cash-flows; including key financial figures as well as the split of fixed and variable costs. It was designed for project developers and policy makers to understand the economics behind mini-grids and to calculate their profitability. The model can consider cash-flows from different sites and consolidate the cash-flows of each site, and illustrate a mini-grid company's income statement and balance sheet through displaying financial indicators like project IRR, and Net Present Value (NPV). The retail tariff calculation tool [78] helps to determine average tariff levels for covering the costs and accommodates various inputs in order to calculate appropriate retail tariffs. Solar PV–diesel hybrid business planning checklist [177] tool provides the possibility to project cash flows, estimate revenues and project returns for small power projects and contains a checklist for the major parameters related to the development of technically feasible and economically viable SPV-hybrid business cases for power generation in off-grid areas. For each of these parameters, this checklist presents general specifications and critical issues/recommendations, which should be taken into consideration.

Odyssey [178] allows mini-grid practitioners to develop, finance, and manage distributed energy projects at scale. It is an online platform that compiles projects including load demand, generation capacity, project capex, and revenues for both project sites and project portfolios. It also links developers to procurement platforms, financers and offers monitoring of financial performance. It is considered the best-in-industry software to efficiently develop and evaluate projects at scale, and although their model doesn't include functionality for social impact or market assessment, it has been used in the methodology and is discussed in more detail in section 3.7

2.5.3.3 Microgrid operations and management tools

Many mini and microgrids develop their own software for operation and maintenance, while other standardized tools exist for monitoring and evaluation, data capture and analysis or customer management for efficient mini-grid operation. For example, the PRODUSE manual [179] includes a step by step guide on integrating elements for promoting productive uses of energy in electrification projects, which includes an Impact Monitoring and Evaluation Guide giving guidance for the design and implementation of different types of evaluations of the impact of productive use of electricity, ranging from qualitative to rigorous quantitative methodologies.

Several smart meter suppliers provide cloud-based remote metering and payments system with online platforms for analysing metering data, Lumeter [180], Steamaco [16] and Sparkmeter [181], which enables utilities to implement pre-payment as well as real time monitoring and control on microgrids and central grids alike. The accounting platform of these providers enhances the meter's functionality by including payment management features like generation of encrypted tokens for the meters, recording transactions across various meters, managing customers and agents, providing meter top-up data and analysis over a period of time.

Other tools relevant for specific mini-grid operation and maintenance activities include: the IFC's Environmental, Health and Safety guidelines [182]; templates for procedures and contents for mini-grid generation/distribution licenses and Power Purchase Agreements[78]; or templates from the UNFCC to calculate CO_2 emissions from Diesel [183] or electricity consumption [184]. Organisational management and strategy tools include cooperative assessment tools [185] and the Organizational Capacity Assessment Tool (OCAT) [186] which helps non-profits assess their operational capacity and identify strengths and areas for improvement. Although such tools would be useful to a microgrid developer for specific operational considerations or challenges, they do not link directly to the business planning functionality this thesis proposes.

Table 6 summary of key microgrid design and business planning tools

Tool	Advantages	Disadvantages/Limitations
Microgrid technical and system design tools		
HOMERPro	Industry standard for microgrid design, allows component sizing through optimisation, cash flow forecasting, and sensitivity analysis. Detailed database of components.	Doesn't design or specify ancillary components. Doesn't provide a detailed balance sheet for a microgrid business. Licensing costs
SMA off-grid calculator	Takes all technical specifications for various components into account and provides relevant data for a cost-effective assessment of the system. Ability to Import meteorological data and load profiles. Optimisation capabilities.	Although can design and specify components for a stand-alone off-grid PV system, not specifically designed for microgrids. Gives a good technical design but doesn't give insight into cash flows or business modelling for microgrids.
Nsol, Paladin, ETAP	Technical analysis including operating costs and system behaviour, power systems simulation and modelling, analysis and optimisation of power system performance.	Generic electrical analysis software, useful for distribution gird modelling, but more suitable for main grid networks rather than microgrid systems.
PVSyst	Ability to design and simulate Stand-alone PV systems. Extensive libraries of PV modules and inverters and batteries quickly design a PV power system and estimate hourly, monthly and yearly energy production numbers	Not specifically for minigrids, can't design distribution grids or distribution losses, doesn't Gives a return on investment, but can't model minigrid tariffs.
Microgrid financial planning and business model tools		
Business model canvas tool	Easily allows entrepreneurs to sketch out and test the viability of business model quickly. Free with significant online support materials available.	High level planning, not enough detail to produce an investable business model. No cash flow forecasting capabilities. Designed for generic SMEs, not specifically for microgrids.
RETScreen	Design and management software system for energy efficiency, renewable energy and cogeneration projects. Feasibility analysis Energy Usage, Emission, Cost, and Risks	Designed for grid connected applications, includes all Renewable Energy Technologies, and not focused specifically on solar off-grid projects

Cost of Renewable Energy Spreadsheet Tool (CREST)	Economic, cash-flow models designed to assess project economics for renewable energy projects. Ability to change ownership models (either a taxable (private sector investor) or non-taxable (government, non-profit, or cooperative) entity, A range in the level of detail for capital and operating cost inputs	More suited to grid connected renewable energy projects in the USA, specifically designed to model cost-based incentives, and evaluate the impact of state and federal support structures on renewable energy. Not specific to microgrids.
IRENA Project Navigator	Comprehensive, easily accessible, and practical information, tools and guidance to assist in the development of bankable renewable energy projects. Project lifecycle process structured in distinct phases. Easy-to-access knowledge materials for each renewable energy technology featuring practical tools, real-life case studies and industry best practices.	Covers all technologies and scales of deployment, as a result doesn't provide specific insights on minigrids, such as ability to model different tariffs. Although caters for off grid systems, main focus is grid connected. No PUE applications.
Power and Tariff Calculation Tool for Solar Mini-grids in Indonesia	Specifically for solar mini-grids, estimates the capacity of the solar mini-grid (generation and storage), investment and the cost of electricity. Electricity costs are calculated based on the general practice in rural.	Specifically for Indonesia, limited application to other contexts. Assumes mini-grids are community managed, doesn't allow other ownership levels.
Odyssey	Industry standard for mini-grid development, allows all techno-economic inputs, outputting a standardised financial model. Integrates online with industry standard HOMERPro. Connects project developers with potential funders, developing remote monitoring functionality to update financial models.	Relatively new software so some bugs and issues which are being resolved. Limited in geographic scope for investors, mainly focussed on Nigeria. Currently no financing or procurement options in Malawi.
Microgrid operations and management tools		
PRODUSE manual	improving the available toolkit for the impact evaluation of electrification programmes	Data to inform the study only available from Benin, Ghana and Uganda. PUE is a key area of making microgrids sustainable, but only one part of the picture.
Smart Meter software	Real time data capture on demand and revenue of microgrid customers. Most have chart and report making functionality for analysis.	Although providing much needed data, the software doesn't yet provide advice on using the data to inform business models or microgrid financial planning.

The tools presented above can support a microgrid planner or practitioner with numerous perspectives of mini and microgrid design, operation, development, and financial planning. The methodology proposed in this thesis uses or follows similar processes to these tools, but it offers a higher-level assessment of microgrid deployment in a region or nation, with a focus on early stage developments. Furthermore, very few of these tools have been used in Malawi, providing critical insight into the country's emerging microgrid sector.

2.6 Chapter summary

This chapter has provided a detailed literature review with the purpose of mapping the landscape of existing solar microgrid research, including definitions and global trends. Social enterprise definitions, related to solar microgrids, and the currently understanding and experiences of measuring the social impact of solar microgrids has also been covered. A summary of existing academic and industry research collaborations in the field of solar mini and microgrids, peer reviewed academic literature, and planning tools in the field of SMSE has also been presented. The purpose of the chapter has been to provide a robust justification for the objectives of this thesis, as well as identifying the gap in academic literature and state of the art industry practice where the contribution this thesis makes is placed.

The research gaps identified from the literature in relation to this study are: a lack of robust academic discourse that explores, systematically interrogates, and quantitatively assesses the business feasibility of social enterprises within the context of renewable energy or solar microgrid applications; few methodologies and planning tools specifically focused on solar microgrids, with none that could be found that holistically allow feasibility assessment of solar microgrid deployment and operation at multiple scales utilising primary data; a focus on technical and economic performance tracking frameworks for minigrids with a gap in understanding on the social impacts of such systems; and a general lack of primary data from active mini and microgrid projects published in academic literature, with almost none in Malawi.

The literature review has shown that although microgrids are emerging as feasible solutions to handle local energy systems, several factors influence the development of such systems, such as technical, economic, social, and regulatory issues. Despite significant research existing in the themes of mini and microgrids globally, few holistic methodologies for assessing the feasibility of solar microgrid exist, with none identified that combine social impact quantification with market assessment and financial modelling at scale, to gain a full picture of the impact and sustainability a SMSE can offer. Furthermore, a methodology that integrates design and feasibility of a single site, with a market assessment on a regional or national level to inform scale up financial planning has not been identified. In addition, there is a dearth of data driven research on microgrids in Malawi that this thesis will address.

Following the identification of research gaps and formulation of research questions and objectives presented above, the next chapter proposes a methodology to assess the feasibility of solar microgrids operating under a social enterprise framework, which is then used on a case study in Chapter 4 in order to answer the research questions posed above.

3 Methodology for assessing the feasibility of a Solar Microgrid Social Enterprise in SSA

Having established the relevance of solar microgrids and social enterprises to address the challenges of energy access in SSA, this section outlines a methodology to assess the feasibility of solar microgrids operating under a social enterprise framework to achieve SDG7 in a sustainable manner.

A social enterprise must perform two functions to fulfil its purpose: be financially sustainable (a successful enterprise) and provide intended social benefits to the community it serves. Accordingly, the methodology proposed in this thesis has two key objectives:

- to determine the financial sustainability of a SMSE operating at scale;
- to measure and understand the level of social impact delivered by SMSEs to the communities they serve.

The methodology also provides recommendations and methods for piloting microgrid sites in order to track their performance on technical, economic and social impact domains. This analysis of primary project data informs SMSE operations and planning, and can also be used as inputs to repeat the methodology. Such an iterative approach reduces uncertainty as desk-based assumptions are replaced with field gathered primary data, with the methodology refined and its validity and utility increased through each iteration. Accordingly, the methodology can be utilised in countries where no microgrids exist, or where some pilot projects are operational, and becomes a useful tool at any early stage of a microgrid programme.

This chapter starts with identifying users or stakeholders who will likely find utility in the methodology, and states pre-requisite activities for conducting the methodology, including a list of assumptions used in the development of the methodology. An overview of the methodology is presented, before a detailed explanation given of each methodological step: assessing financial sustainability and piloting, monitoring and evaluation using a social impact focused Key Performance Indicator framework.

3.1 Users of the methodology

The methodology will have utility for a wide range of stakeholders intending to research, implement, devise policies or make other changes in the microgrid ecosystem to progress their uptake and efficacy in serving rural populations living in energy poverty. A summary of these stakeholders and how they may use the methodology, including academic researchers, solar microgrid practitioners in the private sector, representatives from government and the wider public sector, and those working in the third sector including NGOs and charities, is summarised in Table 7. Stakeholders can use different sections of the methodology in different ways: for example, microgrid practitioners will find value in the market assessment stage to inform their business strategies, while governments and public sector bodies will find utility in the feasibility checks presented to understand in more detail barriers preventing microgrids from scaling, in order to enact changes in the enabling environment to accelerate their uptake. Academic communities will find value in the data analysis and methodological frameworks presented in order to use the process in different contexts and countries to test the methodology and further knowledge and understanding in the microgrid sector from an academic perspective.

Table 7: Overview of methodology users

Stakeholder	Use of Methodology
Researchers, Academia	Microgrids for rural electrification are increasing in prominence in literature. Transdisciplinary partnerships between academia, private and public sectors are becoming more essential for progressing microgrid deployment, contributing to their sustainability and understanding their social impact.
Private Sector: microgrid companies, existing or planned	The methodology and methods within it will be useful for a company starting out to decide whether solar microgrids are a viable strategic direction to pursue. Existing solar microgrid companies can feed existing data into the methodology to refine their business strategy.
Public Sector: national or local governments	Mini and microgrids are forming and increasing contribution to rural electrification strategies. Developing effective policies for accelerated and sustainable rural electrification at a regional and national level requires robust scientific methodologies and analysis of primary data.
Third Sector: NGOs	Many NGOs are already engaged in energy access initiatives, and are considering setting up social enterprise arms to complement their work. The methodology can inform the market, and provide recommendations for pursing their microgrid initiatives.

3.2 Methodology Overview

The methodology utilises established tools and techniques within a novel methodological approach to assess the financial feasibility and social impact of SMSEs operating at a regional and national scale. Figure 14 outlines diagrammatically the steps of the methodology, while key process are discussed below.

1. Novel methodological steps to assess the financial sustainability of a solar microgrid enterprise in a given context, through three linked work areas:
    a. Conducting a feasibility study for a defined use case solar microgrid
    b. Assessing the regional or national market potential
    c. Modelling business scale up scenarios
2. A novel framework to assess the performance and impact of piloted solar microgrids, using a social impact focussed Key Performance Indicator framework. This is used to monitor and evaluate existing solar microgrids in technical, economic and social domains to increase understanding of performance and determine if they can provide social benefit, assessed with respect to local contexts and delivery models used.
3. Utilising the outputs of both previous sections to inform business models for SMSE and the wider microgrid ecosystem.

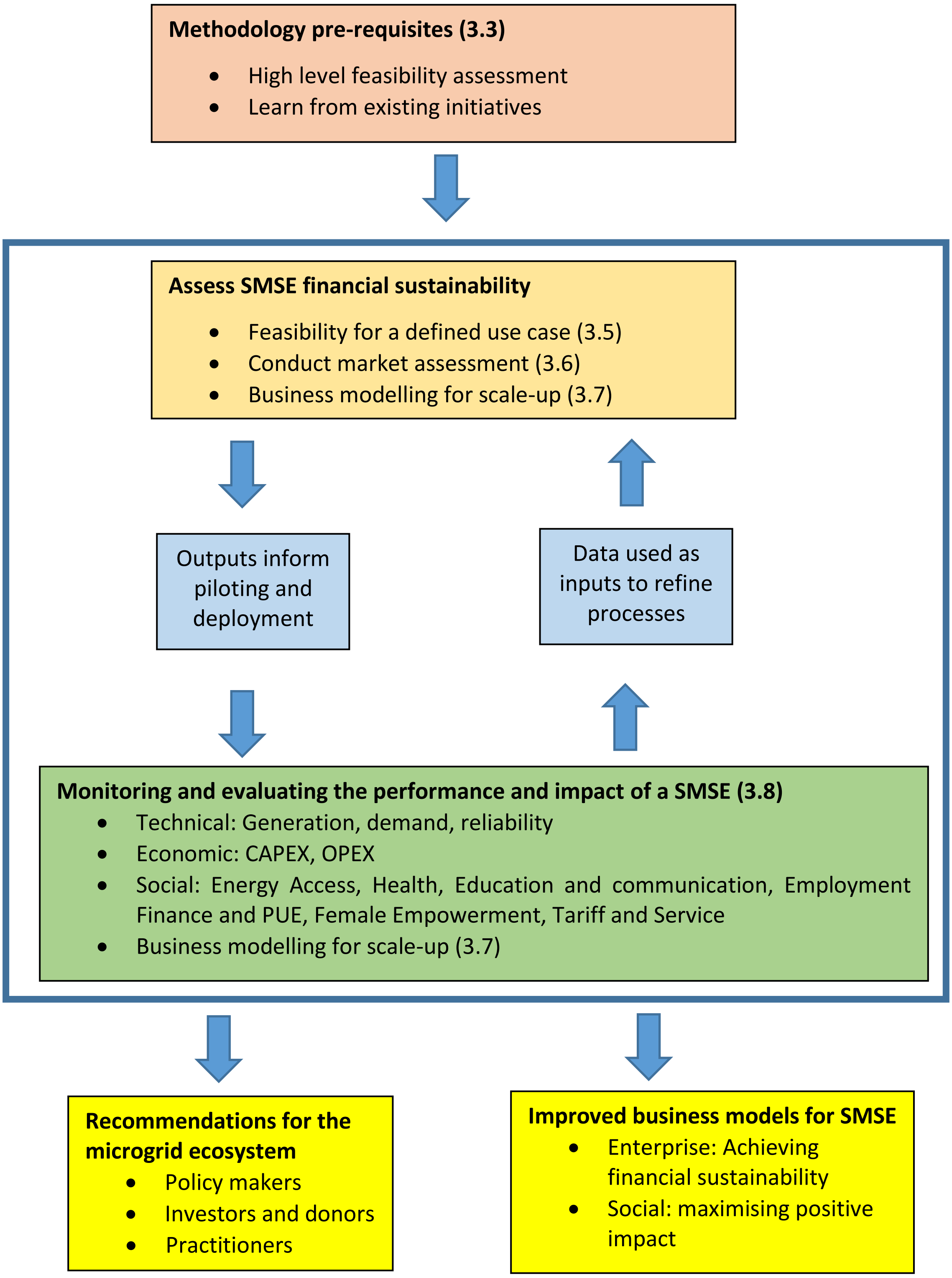


Figure 14 Methodology Overview

The methodology is intended to be used at different stages of microgrid deployment. For an early stage, where no microgrids are yet in operation, primary data is gathered through surveys and existing literature and stakeholder interviews. As more microgrids are deployed, data gathered from the systems can be used to inform and refine the methodology. The methodology can thus be used in an iterative manner, gathering further data as more microgrids are deployed, increasing the feasibility and efficiency of a SMSE programme at each step. In Chapter 4, the methodology is tested and validated on an active case study in Malawi, where a solar microgrid social enterprise has been designed and piloted utilising the methodological steps presented. The data analysis offers further novelty in an area where a paucity of published data exists.

3.3 Pre-requisite methodology steps

In order for the methodology to have maximum utility for users, it is necessary to specify and locate how the research process fit within the wider picture of microgrid deployment in the location of study. Pre-requisite activities are completed prior to the main methodology steps, firstly as a check to ensure the study is worthwhile conducting, and secondly to gather secondary case study data to inform the study. Accordingly, a high-level assessment of solar microgrid feasibility is conducted to determine if the methodology is appropriate for the given country/region, and learning from existing microgrid initiatives informs proceeding choices and assumptions used in the methodology.

3.3.1 High level assessment of solar microgrid feasibility for the country/region

The application of this methodology assumes that the country or region within which it will be used has potential for SMSE, and is designed for use in where little or no microgrid deployment exists. To fully define the countries and regions where solar microgrids have potential for deployment, a global market assessment for solar microgrids should be carried out, following methodologies such as used for small wind [187] or electric cooking [188]. The process would consider a variety of indicators that would make solar microgrids appropriate for deployment, and use Multi Criteria Decision Making Analysis to score and weight indicators to rank countries based on their suitability for solar microgrids. A filtering exercise would then assess whether solar microgrids should be considered as a potential technology for rural electrification in a given geographical location or context. Indicators such as level of grid access, solar resource, population density, and current country-level progress towards SDG7 should be considered, and if certain criteria are not met, resources should not be invested to continue the viability assessment. This research is deemed out with the scope of this thesis; however, the following indicators are listed as pre-cursers for this methodology to be appropriate at a country level to be used in.

- The focus of the methodology is on Low-Income countries in Sub-Saharan Africa, defined by the World Bank, as nations that have a per capita Gross National Income (GNI) of less than \$1,026 [189].
- The methodology is suitable for countries with a low access to electricity rate (<30%) according to World Bank data [190].
- The methodology is intentionally intended to be of use for early stage or nascent microgrids sectors, and only countries should be considered where very few microgrids have been deployed (suggested as <20).

3.3.2 Learn from existing initiatives

In order to inform early steps of the methodology, case studies of solar microgrid initiatives either in the country of interest, or nearby regional countries, are analysed to identify key factors for success and barriers to implementation in the country or region of interest. Projects are chosen to offer a variety of rural electrification approaches involving variant approaches in technical solutions (e.g., AC versus DC); in developer/investor/operator (private, social, community enterprises); and in business models.

Field visits to partner organisations are carried out to analyse first-hand the experiences of solar microgrid development. Semi-structured interviews with project managers, consisting of open-ended questions relating to the organisation as a whole, technical aspects and business models of their microgrids are used, and notes are transcribed and thematically coded to draw out key themes for case study style representation. Additionally, project managers are asked to provide details of tariffs, system and business costs, used to model local systems.

The purpose of this primary research is to gain insight on active real life projects, acquire a perspective on the realities of microgrid implementation, discover contributing factors to success or challenges of microgrid implementation, and draw comparisons between the influencing parameters and enabling environment in surrounding contexts. Analysis of each initiative draws out commonalities and differences between the initiatives to inform decisions of what may work on not in the region of observation.

3.4 Assessing SMSE financial sustainability: Overview

The first methodology section assesses the financial sustainability of an SMSE in a given country context, and comprises conducting a feasibility study of a defined microgrid use case, assessing the market potential, and conducting business scale up modelling. Although these steps follow established tools and methods, the linking up of all three in a unified framework presented here is new. Financial sustainability assessment includes inputs, processes, outputs and feasibility checks:

- **Inputs:** Data and assumptions required to inform the processes, gained from desk research, primary in-country data collection, or measured data from pilot projects.
- **Processes:** how the data is analysed, changed and adapted to provide outputs, inform feasibility checks, checks and inputs for other methodology steps.
- **Output:** key results from processes providing insight to understanding the economic viability of the enterprise, and the basis of the feasibility check
- **Feasibility check:** At each stage, a feasibility check is conducted to determine the level of feasibility a SMSE offers, and examine assumptions and processes to explore the factors influencing feasibility to provide recommendations to increase SMSE feasibility and ultimate sustainability.

At each occurrence of a feasibility check, an analysis of the results and findings of the processes to achieve it provide insight to inform business strategies as well as interventions within the SMSE enabling environment to address barriers preventing feasibility, or improve the likely sustainability of the SMSE. The methodology can thus be used as a planning tool for both practitioners and policy decision makers to accelerate SMSE deployment in a sustainable manner. A summary of the key steps of the methodology to assess financial sustainability is summarised in Table 8, with the inputs, processes, outputs and feasibility check specified.

Table 8: Assessing Financial Sustainability of SMSE

Inputs	Processes	Outputs	Feasibility Check
1. Feasibility study for a defined use case (Section 3.5)			
Site prospecting data Load Profiles Solar Resource Local component Costs Ability and Willingness to Pay	Site Selection System Design Tariff Calculation Financial modelling	CAPEX OPEX Cost Reflective Tariff	Cost Reflective Tariff vs Ability and Willingness to Pay Local Supplier Availability
2. Market assessment at a regional or national scale (Section 3.6)			
CAPEX OPEX Load Profiles Geospatial data Competitor technology costs	Techno-economic modelling Geospatial modelling Ecosystem Mapping	Market Potential and deployment cost Site Mapping Ecosystem Barrier identification	Adequate Market Potential Cost competitive deployment against competitor technologies Favourable Ecosystem
3. Business modelling at scale (Section 3.7)			
CAPEX at Scale OPEX at Scale Market Potential Multiple site load profiles	Site selection for fleet of microgrids System design of multiple sites Cash-flow forecasting at scale	Scale up scenarios Detailed Financial planning and business model Operational strategies	Scaled operations economically viable

3.5 Feasibility study for defined use case

A site-specific feasibility study to determine an indicative system design based on realistic user demand is required to output local costs of developing, installing and maintaining a solar microgrid in the region of interest. Outputs from this methodology step are used for subsequent steps in market assessment and business modelling at scale, and a comparison of cost reflective tariff with customer ability and willingness to pay acts as a high-level indicator of microgrid feasibility. The proposed method for system design and business planning has been trialed [191]; it builds on industry standards [192] [81] and employs two key elements:

- a qualitative site selection and customer survey exercise, utilising enumerator fieldwork to provide metrics for project feasibility; and
- a quantitative techno-economic modelling, focusing on technical and financial feasibility to inform a viable business model.

3.5.1 Input: Site prospecting data

The site selected for microgrid implementation has significant impact, among other factors, on attracting both public and private investments and the overall sustainability of the system. A careful and thorough evaluation of potential sites for implementation is required to deliver both social and economic benefits to potential power consumers, as well as boost investment from the public and private sectors [193].

The site selection process scores potential villages in an identified district or region based on strategic indicators such as distance to grid, population density, accessibility and economic activities. Structured questionnaires via trained enumerators (targeted to households and businesses in the chosen site) input into key system design metrics and include indicators such as: current and expected energy use estimation, ability and willingness to pay, existing and aspirational businesses activity and other informative social and demographic indicators. An overview of the categories, indicators and guidance for site selection is given in Table 9.

Table 9: Site selection parameter

Category	Indicators	Guidance	Weighting
Location of Installation	Distance to grid	Should be unlikely to be grid connected in the near future	HIGH
	Transmission distance based on population distribution	Densely populated, (houses close together) is better than sparse	MEDIUM
	Accessibility and terrain	Should be easy to access	HIGH
Productivity	e.g. Water Pumping, cottage industry, commercial activities and irrigation	The more potential productive uses the better	HIGH
Payment for services	Ability and Willingness to pay, economic activities in the village	Higher income levels better	HIGH
Magnitude of potential power consumers	Households, businesses, anchor loads, government buildings, administrative units, development organisations	The more consumers the better –30 minimum	HIGH
Security	Petty theft, cattle theft, banditry	High security is better	MEDIUM
Local Capacity	Existence of community organisations and social infrastructure	The more evidence of community cohesion/organisation the better	MEDIUM
Local Experience	Existing activity, local knowledge	Developers may have preferences of areas to work/not work in	LOW
Mobile Signal	Quality of mobile signal	The microgrid will potentially use mobile money, a mobile signal is required	MEDIUM

3.5.2 Input: Energy use surveys to determine load profiles

Appropriate dimensioning of microgrid generation systems and detailed business planning requires accurate knowledge of expected consumer demand. There is a lack of standard measured load profiles from microgrids [194] and the most common method for estimating electricity usage is through determining current and future energy demand via surveys. The process improves system sizing, and the accuracy of CAPEX estimation and financial modelling of delivery models for SMSEs.

Load profiles for use in system design are created through a baseline survey of potential microgrid customers in the location for the proposed site to assess microgrid electricity demand. Customers are asked about current use of electricity, appliance ownership and frequency and duration of use. Alternative energy use such as dry cell batteries and diesel fuel are also assessed to determine if electricity can offer a better alternative. Aspirational energy is assessed through asking which appliances customers hope to acquire once they have electricity access, although no time period is specified. Energy use surveys are common practise, but account for most of the uncertainty associated with load profiling of microgrids, with potential aggregate error in energy prediction per day estimated to be as high as 305% [195].

Based on the survey data, power rating and running times were extracted for each appliance and used to construct appliance-specific load profiles. An average customer load profile was constructed so as to generate a load profile for the total household load. The average household load profile is constructed by considering all appliances which are used at time i. The calculation for the load (Ei) at time i is shown in Eq. (1).

$$E_i = \sum_m^n P_{m,i} \quad (1)$$

Note that $P_{m,i}$ can be decomposed into $P_a \times K_a$ where P_a is the power rating of the appliance and K_a is the loading percent of the appliance. The loading percent reflects that certain appliances such as refrigerators do not continuously consume rated power. To construct survey-based load profile representing all customers, all appliance load profiles for the interviewed customers were aggregated into a single load profile. The output of this step is daily load profiles, displaying peak energy use at hourly intervals for total demand. An example load profile for a mini-grid is given in Figure 15**Error! Reference source not found.**.

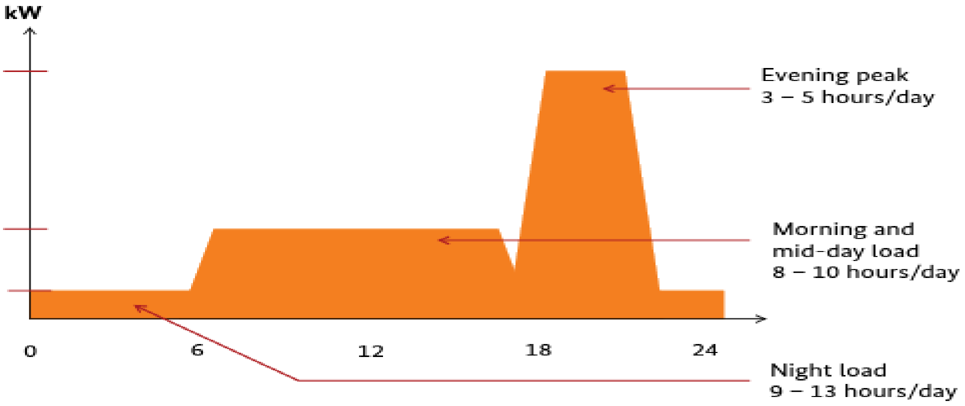


Figure 15 Typical mini-grid load profile in rural areas [192]

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3.5.3 Input: Solar resource

The generation output of the solar microgrid is directly related to the available solar resource, and therefore a clear understanding of the solar resource in the microgrid location informs system design processes. Several online solar resource datasets are available to system designers, with the most commonly used outlined in Table 10.

Table 10 Online tools to determine Solar Resource for microgrid design

Solar Resource	Description
Global Solar Atlas [196]	Solar resource and PV power potential maps and GIS data are available for 147 countries (eligible for the support from Development Assistance Committee acting under OECD) and selected regions. The maps and data have been prepared by Solargis for The World Bank. They are provided under CC BY 4.0 license
Renewables Ninja [197]	Renewables ninja allows users to run simulations of hourly power output from wind and solar power plants located anywhere in the world. The tool has been built to help make scientific-quality weather and energy data available to a wider community. The ninja works by taking weather data from global reanalysis models and satellite observations. The two data sources used by the tool are: NASA MERRA reanalysis and CM-SAF's SARAH dataset. Solar irradiance data is converted into power output using the GSEE model (Global Solar Energy Estimator)
Solar and Wind Resource Maps [198]	The Solar and Wind Energy Resource Assessment (SWERA) initiative brings together solar and wind energy resource data sets and analysis tools from a number of international organizations in a dynamic user-oriented environment. The information and data provided on the site are freely available to the public and intended to support the work of policy makers, project planners, research analysts and investors.

IRENA Global Atlas for Renewable Energy [199]	The Global Atlas for Renewable Energy is an initiative coordinated by IRENA, aimed at closing the gap between nations having access to the necessary datasets, expertise and financial support to evaluate their national renewable energy potential, and those countries lacking such elements. The Global Atlas facilitates a first screening of areas of opportunity where further assessments can be of particular relevance. Currently, the initiative includes maps on solar, wind, geothermal and bioenergy resources along with one marine energy map. The initiative will eventually encompass all renewable energy resources, providing global coverage through the first-ever Global Atlas for Renewable Energy.
PVGIS [200]	PVGIS is a data platform hosted by the EU Joint Research Commission. PVGIS offers data on solar irradiation for Europe, Africa and Asia. Geographic information on monthly or daily global irradiation data can be presented on a google-based map. A quick PV yield estimation can also be calculated, both on- and off-grid.

Solar resource data is generally given in terms of GHI (Global Horizontal Irradiance) with average daily (kWh/m^2/day) values given as an analysis of 20 years of satellite data (1994-2004). For this study, the solar resource is automatically obtained through HOMER pro from NASA for the given latitude and longitude of the site location. HOMER uses the Solar GHI Resource to calculate flat panel PV array output. GHI is the sum of beam radiation (also called direct normal irradiance or DNI), diffuse irradiance, and ground-reflected radiation [201]. Solar resource data from NASA Surface meteorology and Solar Energy, Global horizontal radiation, monthly averaged values over 22 year period (July 1983 – June 2005) are used for system design and modelling.

3.5.4 Input: Local component costs and OPEX estimates

CAPEX calculations require cost estimates for microgrid components, including generation, storage, control, distribution, house wiring and smart meters. For the first time the methodology is being implemented, quotes are obtained from local or international suppliers. The accuracy of data can be low as suppliers may not be interested to give detailed costs if they are not actually providing the equipment. Consideration must be given if quotes are being obtained from international suppliers for transport and importation taxes. Benchmarking studies [26] [211] provide comparison costs for global or regional costs but don’t accurately reflect local costs, increasing uncertainty of assumptions.

For further iterations of the methodology, component costs are obtained from previous pilot projects, averaging from several installations. Consideration is given for future price trends, as the cost of solar PV and batteries has been steadily declining and is expected to continue to do so as shown in Figure 4 **Error! Reference source not found.**. Costs and availability of local components can be a limiting factor for a nascent minigrid market and are highlighted as a feasibility check at the end of this section, with recommendations given for overcoming barriers presented in underdeveloped supply chains.

System and business modelling in proceeding sections requires input on operational costs to inform tariff calculations. Initially estimates are gained through quotes from smart meter providers and maintenance contractors, as well as conversations with practitioners on staff and transport costs for reaching microgrid sites. As pilot data is gained the primary data can be utilised, as described in Section 3.8.

3.5.5 Input: Ability and Willingness to Pay

Ability to pay (ATP) refers to a customer's financial means to pay for a product or service, while willingness to pay (WTP) is more often used when referring to a customer's inclination to purchase a product or service at a certain price. The National Rural Electric Cooperative Association defines Willingness to Pay (WTP) as "the maximum amount that an individual indicates that he or she is willing to pay for a good or service" [203]. Calculating ATP and WTP for microgrids is the subject of several research papers [204]–[206], for this methodology the assumption is stated that financial sustainability of a microgrid project depends largely on the ability of users to pay a tariff that generates enough revenue to cover the costs of operations, maintenance and repairs for the mini-grid system [207]. Additionally, a microgrid is more likely to be financially sustainable if it can provide a superior level of service (i.e., more reliable, more hours of electricity, brighter lights, less indoor pollution) for a tariff that is similar and ideally lower than a household's current energy expenditures. Furthermore, following the defining characteristics of an SMSE outlined 2.3.2, consideration should be given to the affordability of all members of the community that want a connection.

Surveys determine the current spend on energy services that the microgrid will replace (ATP), while further questions explore how willing potential customers are to pay for the microgrid service (WTP). Examining ATP and WTP with cost reflective tariffs calibrates the feasibility of the system design to sustainably provide tiers of service within the budget defined by revenue collections, and play a pivotal role in the methodology. WTP surveys are accomplished through the following approaches:

- A survey of expressed WTP: This is the maximum amount that a person says they are willing to pay for different tiers of electricity.
- A survey of ATP: This is the actual amount people already pay for kerosene lamps, candles, flashlight batteries, diesel for a home generator or other substitutes for microgrid electricity.

Data from these surveys are compiled to determine average values (generally in monetary units per month for a certain quality of service or per kWh) compared with the Cost Reflective Tariff calculated in the proceeding steps to serve as feasibility check. Depending on data available, ATP or WTP can be used, accordingly for the proceeding step the term Ability and Willingness to Pay (AWTP) is used.

3.5.6 Process: Site selection

Site prospecting data is analysed with responses for each indicator and given a score out of 5, then normalised from 0 to 1 to allow for binary responses. Total scores allow villages to be ranked. Discussions are held with enumerators following the fieldwork to compare top scoring villages with their subjective opinions of priority villages. Further discussions are held with national or district executive staff to determine which of the sites found are likely to receive mains grid power in the near future, any with a high likelihood are eliminated, leaving the highest scoring remaining village as the destination for the demand surveys. The result is a chosen site to conduct the defined use case feasibility, as well as a ranked list of further sites to consider for development.

3.5.7 Process: System design and cost

Microgrid generation and distribution systems are designed utilising inputs, sizing key components of PV generation and batteries, and producing a bill of quantities to determine system cost. The methodology uses commercial simulation and optimisation HOMER Pro [164] to design the generation system, which simulates the microgrid system operation by calculating the energy balance on an hourly basis over the entire year across all possible system configurations. HOMERPro's optimisation functionality ranks system configurations that meet (or exceed) the specified energy demand in terms of energy production according to Net Present Cost (NPC). The NPC considers all expected costs related to the implementation and operation of the energy system over its life-time, adjusted for discount rates and inflation. HOMER takes the inputs of total hourly load profile, solar resource, and local component cost and specifications and using its optimisation algorithm, sizes the system components based on lowest NPC. Outputs comprise system component sizes, as well as total CAPEX which is used for the proceeding steps of the methodology.

The distribution system is designed through taking GPS coordinates of customer locations, and utilising a least fit algorithm developed by the University of Strathclyde [208] to locate the poles and estimate the cable length. Currently the tool can produce a mini-grid reticulation (network) design, showing spans of customer and utility poles interconnected with cable conductors to form a grid network. The tool's automated reticulation functionality is based on the existing design methods employed by PowerGen network designers, but utilises various algorithms to implement these methods, including Particle Swarm Optimisation. This algorithm is applied to optimize the placement of utility poles in order to minimize the total cable length required for interconnecting customer locations. By iteratively adjusting the positions of particles (representing potential pole locations) based on their individual best positions and the global best position found so far, it effectively guides the search towards a configuration that reduces the overall cable length while ensuring connectivity between all customer locations. From the distribution grid design a bill of quantities is produced, which is used to request quotes from local suppliers. As pilot data is collected, deployment costs are used to increase accuracy.

The outputs of HOMERPro and the distribution system design tool are used to inform a final system design, specifying ancillary components and producing an itemised bill of quantities, utilising the following international standards:

- IEEE 1546.4: Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems [209]
- IEEE 1526: Testing the Performance of Stand-Alone Photovoltaic Systems [210]
- IEC TS 62257: Recommendations for renewable energy and hybrid systems for rural electrification [211]

3.5.8 Process: Cost Reflective Tariff calculation

The overarching philosophy of a SMSE is to provide a sustainable, reliable electricity supply that is affordable to all members of the local community that want it. The technical design and tariff setting process therefore adheres to the following key principles:

1. The electricity supply provided should meet the needs of households and small businesses expressed through detailed community engagement.
2. The service should be superior quality and cheaper than alternative energy solutions available in the area.
3. The microgrid must have a sustainable, long-term business model with tariffs designed to cover all social economic costs (based on detailed analysis of forecast revenues and costs)

Following a system design and CAPEX and OPEX estimates achieved through prior steps, a Cost Reflective Tariff (CRT) is calculated to inform at what cost electricity must be sold to generate sufficient revenue for the microgrid to be economically viable. CRT is defined as a tariff that reflects the full cost of providing electricity to consumers, including the installation, maintenance and operation of a mini-grid [212].

The tariff is calculated on a 5-year period by dividing the Net Present Value (NPV) of the revenue requirement by the NPV of the billed consumption. Figure 16 diagrammatically represents the steps and parameters required to calculate a microgrid tariff.

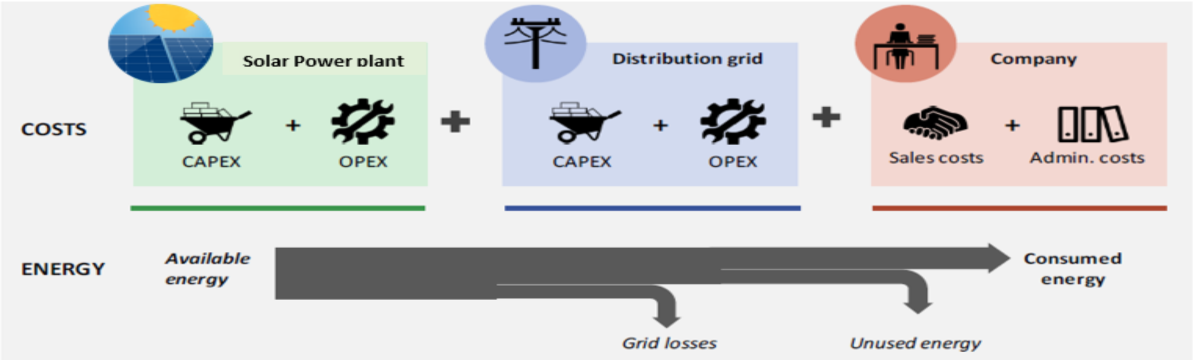

Figure 16 Main cost factors of a solar micro-grid company and relevant electricity metrics

Once calculated, tariffs can then be compared to the ability and willingness to pay of the as a feasibility check for the microgrid. The formula used to calculate the CRT is shown in equation 2.

$$CRT = \frac{RR}{E_t} \qquad (2)$$

Where:

- CRT (Cost Reflective Tariff)
- RR (Revenue Requirement) = Site based operations cost
- E_t = Total useful electricity generation forecast

Site operational costs related to energy production comprising metering, generation maintenance, distribution maintenance, land rental, site agents, security guard, and fixed and contingency costs. Assumptions must be made if they are to increase in line with inflation, modelled as an annual increase. At this stage, business overheads, depreciation costs, applicable loan repayments and return on capital are not included, as these are considered in business modelling at scale, where several microgrids are included in a portfolio.

The total useful electricity generation forecast is calculated as every unit that is produced and sold. Microgrid systems should be designed to provide enough power to fulfil the electricity demands of the customer segments identified in community engagement. Initially, calculations for daily energy demands and number of customers are determined through surveys conducted at household and business level and come from the inputs of load profiles in section 3.5.2. When available, demand data from existing microgrid pilots can be utilised.

According to [213], With few exceptions, African countries are employing Willing Buyer/Willing Seller and/or Individualized Cost Based Tariff to set mini-grid tariffs. Additionally, [214] states that Cost-reflective tariffs can more effectively attract micro-grid investment by providing a viable means for developers to recoup costs and investors to secure returns, and can thus increase the overall speed of deployment of new micro-grids. At this stage of the methodology the CRT gives a high-level indicator of the minimum tariff needed to cover site-based costs, and is compared to customer ATP as a feasibility check. The CRT is used as guide in business modelling for scale-up to design tariff bundles for different customer segments

3.5.9 Feasibility study for a defined use case: Outputs and feasibility check

Capital and operation costs are key parameters of microgrid implementation as they affect SMSE financial sustainability and investment appetites. Benchmarking studies of mini and microgrid costs such as those provided by the World Bank [202] can be used to check the figures obtained. CAPEX and OPEX outputs are used as inputs for the Market Assessment analysis as well as the Business Scale-up sections of the methodology, in order to test SMSE sustainability at scale, and can be refined as primary data costs from pilot implementation become available.

A full cash flow analysis of financial sustainability is not conducted at this stage, as it is assumed that one single microgrid is unlikely to be implemented on its own, and several will need to be undertaken for the SMSE to reach financial sustainability. Accordingly, feasibility checks at this stage relate to CRT vs AWTP, and availability of local suppliers. Comparing the cost reflective tariffs to customer ability and willingness to pay is analysed to determine if SMSE is a non-starter for the region in terms of unaffordability for the customers. If the CRT is too high, then developers must look at ways to reduce the costs, either through reducing capital costs or finding efficiencies in operational costs, or look for grants or subsidies to improve financials.

Another feasibility check at this stage is the availability of local suppliers: if there are not enough local suppliers then international suppliers will be needed which will increase capital costs. This can be addressed through awareness raising on the potential of microgrids through renewable energy networks or forums. This can be further enhanced through greater understanding of the microgrid potential in the region of question from the outputs of the next methodology section the market assessment. The next step of the methodology conducts a market assessment to determine the potential market and regional potential for scale up.

3.6 Conduct market assessment for solar microgrids at a regional or national scale

Market assessments are widely seen as being key to the planning stages for off-grid energy provision in the developing world [161]. Playing an essential role in an energy planning feasibility study, a market assessment indicates the size of the potential consumer base for a technology, along with their distribution within a given region and the necessary considerations of the economic viability of projects at specific locations. Market assessments also map regulatory, political, cultural and socio-economic factors within the energy access ecosystem that impact sustainable deployment of the technology and proposed business plan under consideration [215]. The quantification of market size and ecosystem mapping are paramount in establishing the business feasibility of a SMSE.

Accordingly, this step of the methodology assesses the market potential at a national or regional level for SMSEs, providing an output that defines geographically where solar microgrids are cost competitive with alternatives, and maps out the regulatory, institutional and economic ecosystem in which implementation will occur. The market assessment provides the next step in evaluating the feasibility of a SMSE business model through assessing cost against competitor technologies, and quantifying the potential for scaling operations, based on previously obtained outputs of the use-case feasibility study.

The market assessment steps of the methodology utilises and builds upon an established methodology [216] [217]follows a two stage process to assess the market for solar microgrids in a given geographic region, namely: quantifying the potential market, and mapping the microgrid ecosystem, outlined in Table 11.

Table 11. Comparison of the two principal stages carried out during this market assessment.

Stage	Key research questions	Data collection techniques	Data processing techniques	Key Outputs
Quantifying the potential market	How scalable are solar minigrids in the region of interest?	Primary data: System configuration; Economic data; Secondary data: national statistics; GIS layers	Energy systems modelling (HOMERPro); Geographic Information Systems	Market size and distribution
Mapping the energy access ecosystem	What are the key risks and barriers preventing these solutions from reaching scale? What can be done to overcome them?	Literature review; Existing experience from previous in-country fieldwork and research	Summarised according to specific themes	Recommendation for targeted interventions

3.6.1 Techno-economic inputs

The market assessment compares the cost of microgrids with competitor technologies at geographic locations. The Levelised cost of energy (LCoE) is used as a metric for comparison and accordingly, input data on microgrid costs, performance and useful delivered energy is required. Accurate data of energy load profiles, component costs, and business operational, management and administrative costs used here for inputs to the techno-economic modelling process are taken from the previous methodology steps outlined in section 3.5. Pilot project data (section 3.8) can also be used as inputs to provide more accurate analysis.

Individual customer load profiles are built from primary survey data, with the number of customers in each microgrid modelled arbitrarily adjusted to provide representative microgrid designs with varying scales of generation capacity in line with case studies found in the existing initiatives. Three models are designed, to cater for high, medium and low demand levels. Each of these cases have a set base capital cost and fixed operations and maintenance cost to reflect the costs of necessary infrastructure, installation and administrative costs associated with operating a microgrid of each size. Competitor technology costs, specifically SHS, diesel generators and grid extension are found from available literature and stakeholder interviews. The methodology can be adapted to include additional renewable competitor technologies such as wind, hydro, or biomass gasification, but is considered out of scope for this thesis. Cost curves are then built in HOMERPro for key components based either on quotes collected in section 3.5.4 or data from pilot projects, which allow HOMERPro to optimise the system design based on resource and cost inputs.

O&M costs are modelled as a combination of the overhead of the operator plus the anticipated maintenance trip costs, per year. Maintenance trip costs at each site are modelled as a function of the accessibility of that site, and the time taken to reach it.

3.6.2 Geospatial inputs

Market potential is quantified over a given geographic area representing the likely region an SMSE will be operating, necessitating the utilisation of geographic information layers. The level of detail methodology users go into will depend on available datasets for the region in question and resources available. Table 12 outlines key geographic layers utilised in the market assessment analysis and their relevance to a solar microgrid market assessment.

Table 12: Key geospatial inputs used for market assessment

Parameter	Units	Why it links to market assessment
Solar Scaled Average	(kWh/m^2/day)	Output of generation and performance of system linked linearly with solar resource
Scaled Average Temperature	(°C)	Battery and PV module performance linked directly to temperature
Diesel Fuel Price	($/L)	If solar microgrids are including diesel, or to calculate competitor technology, diesel price must be known
System O&M trip cost	($/year)	Sites further away will cost more to maintain, and affect the financial feasibility of the sites in question
National Grid	Locations	Microgrids won't compete with grid connections and site earmarked for grid connection
Population density	hh/km^2	Population density affects the number of customers and size of microgrid

The average solar resource data and scaled average temperature are used in the forms available through HOMERPRo, whereas diesel cost data and maintenance trip costs are modelled with the use of travel time and accessibility mapping methodologies developed in [219]. Diesel fuel price maps are assembled through the same methodology as presented in [220] shown in equation 3 and assumptions outlined in Table 13. The cost at a given location is modelled as the pump price of diesel plus the fuel costs of transport of diesel from the nearest pump to the given location, with travel times mapped through the methodology presented in [219].

$$P_l = 2P_d\, c\, t/v \qquad (3)$$

Table 13 Assumptions used for inputs into fuel price modelling.

Variable	Description
P_l	Diesel price at site location (USD)
P_d	Pump price of diesel
c	Average diesel consumption rate of fuel delivery vehicle
t	Travel time from diesel pump to site
v	Volume Capacity of Diesel Fuel per transport vehicle
N/A	USD to local currency exchange rate

Equation 4, with assumptions outlined in Table 14, outlines the calculation made to determine maintenance costs by location. This calculation is based on two maintenance trips per year by the system operator, assuming the rest of the maintenance activities will be carried out by the end-user community at no additional cost to the system operator.

$$C_{O\&M} = 2(P_d ct + N_{Tech} W_{Tech}(t + t_{maint}) + N_{Tech} C_{lodge} t_{day}) + C_{Overhead} \tag{4}$$

Table 14 Assumptions used for calculation to determine maintenance costs

Variable	Description
P_d	Pump price of diesel
c	Average diesel consumption rate of vehicle
t	Travel time from maintenance hub to site
N_{Tech}	Number of Technicians visiting site (inc. driver)
W_{Tech}	Maintenance Technician Hourly Wage
t_{maint}	Maintenance time
C_{lodge}	Lodging Cost per Technician Per Night
t_{day}	Number of days spent on maintenance trip (rounded down) to indicate number of nights of lodging required
$C_{Overhead}$	The overhead cost associated with administering the system of a given size

3.6.3 Ecosystem mapping inputs

Energy access ecosystems are mapped using available relevant literature and previous project case studies relating to energy access, solar PV and micro and minigrid projects in the regions over the last 10 years. Regulatory frameworks relevant to ecosystem mapping specific to solar microgrids are found from relevant institutions including national energy regulatory authorities, Government Energy Departments and up to date energy policies and rural electrification strategies. Further input is informed through informal consultation with private sector, government, NGOs and donors working in the energy access sector, backed up by referenced literature. Semi-structured interviews are employed to collect data from these experts, allowing the interviews to capture respondents knowledge on energy access, microgrids and productive uses of energy, whilst at the same time leaving space to learn more about any specific projects that each interviewee may have been involved with or any other relevant experience they may have been willing to share.

3.6.4 Process: Quantifying the market through techno-economic modelling

This stage of the methodology combines microgrid optimisation software HOMERPro with Geographic Information Systems (GIS) applications utilising a novel mapping and interpolation tool [221]. The mapping tool uses the optimisation process offered through HOMERPro for a series of representative systems, and interpolates results to all locations within a country or region. The combined use of HOMERPro optimisation and GIS mapping builds on parts of a market assessment methodology previously used by Wind Empowerment in Ethiopia [216] and Malawi [217] specifically for small scale wind power systems. A similar geo-spatial study, using the OnSSET tool, has been conducted for Malawi [222] other studies have been conducted in a number of other countries (Ghana [223]and Nigeria [224]) making up a growing body of literature and research regarding geo-spatial technical assessments and planning support methodologies. The market assessment contributes to discussions by focusing in detail on the potential for deployment of microgrids of different sizes, and by quantifying the required investment (CAPEX and OPEX) per person by location.

Figure 17 outlines the system optimisation and mapping process, along with relevant input data and key tools. Three system types are modelled; solar microgrids and diesel microgrids, to allow for cost comparison, and a solar/diesel hybrid microgrid in order to assess where hybridisation may have cost benefits. Table 15 contains the different variables in the analysis.

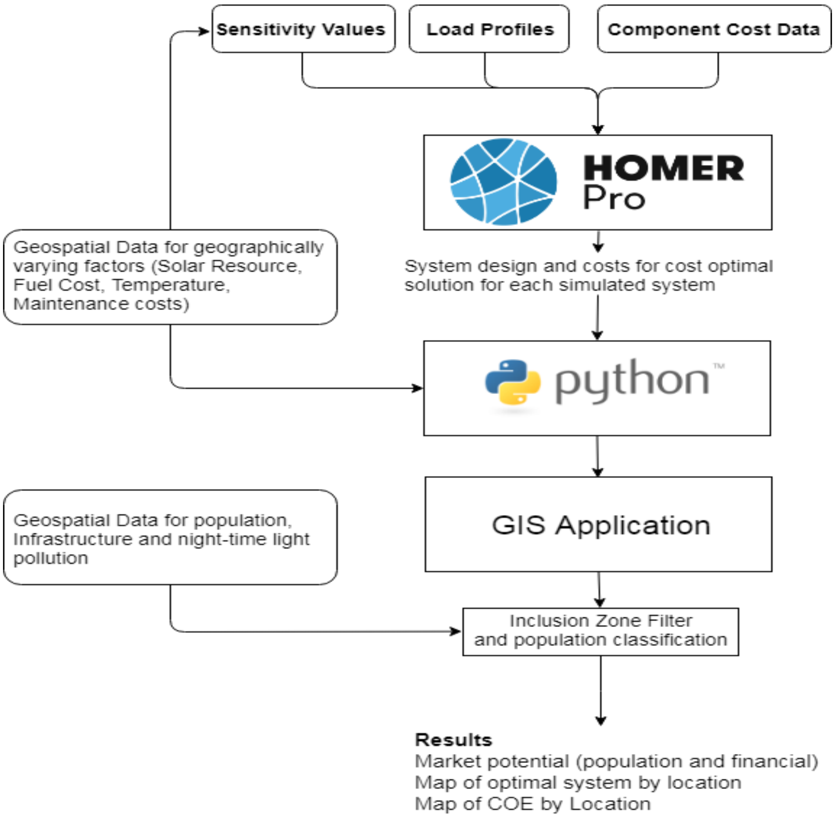

Figure 17 Process flowchart for Quantifying the Market

Table 15 Variables used in market assessment techno-economic modelling

Variable	Units	Relevance/notes
Load profiles	kW/h for each hour of the day	System components sized to meet load profiles
Number of Customers per microgrid	#	Used for calculating market potential, CAPEX and OPEX per customer
PV Unit cost	USD/kW	Informs CAPEX, Net Present Cost and Levelized Cost of Energy for optimisation calculations in HOMERPro. Capital and replacement costs needed
Battery Unit cost	USD/kWh	
Gen-set	USD/kW	
Fixed capital costs	USD	Includes costs for ancillary components, distribution grid, and shipping container

PV and battery specification	Make, model, rating	Output of HOMERPro model is affected by make and model and rating of chosen components
Solar Scaled Average	kWh/m^2/day	Output of generation and performance of system linked linearly with solar resource
Scaled Average Temperature	°C	Battery and PV module performance linked directly to temperature
Diesel Fuel Price	$/L	If solar microgrids are including diesel, or to calculate competitor technology, diesel price must be known
System O&M trip cost	$/year	Sites further away will cost more to maintain, and affect the financial feasibility of the sites in question
Fixed O&M costs	$/year	Site based costs that are not geographically affected
National Grid	Locations	Microgrids won't compete with grid connections and site earmarked for grid connection
Population density	hh/km^2	Population density affects the number of customers and size of microgrid
Night time pollution	Mag/arcsec^2	Used as a proxy filter for grid connection

Simulations are carried out for a number of representative systems. The single microgrid feasibility study outlined in section 3.5 provides cost, demand data and number of customers for a representative microgrid size based on the chosen initial site. Larger and smaller microgrids are included in the modelling to account for different sites of different sizes, giving low, medium and high microgrid size scenarios. Initially the scaling up and down of costs and demand is arbitrary to provide a selection of representative microgrids. Once piloting and detailed site selection provide primary data more accurate data can be input. Additionally, a series of sensitivity values for each of the geographically varying factors are used as inputs for the HOMERPro microgrid design optimisation. Sensitivity values are chosen to maximise the closeness of simulated systems to the systems to be mapped, to minimise any inaccuracies introduced by interpolating between the simulated systems in the mapping process.

With all the inputs identified, HOMERPro is executed and the tabulated results of the optimisation used as inputs into the python interpolation and mapping tool. This tool identifies the least cost design for each unique combination of sensitivity values. The tool then runs a linear interpolation between known outputs (i.e., the optimisation results from each combination of sensitivity values) to achieve a finer data resolution for mapping by generating intermediate results: the closer an imputed value is to a sensitivity value the more accurate it can be considered to be. Once interpolated, the data is mapped across the country or region, using the values from the input maps to determine the combination of sensitivity variables to identify the optimal design (by cost of energy), and the costs associated with a given design in a given location. The interpolation process is iterated across the whole country or region to produce full maps of the area of interest.

Three HOMERPro optimisation runs are performed for both solar microgrids and diesel microgrids, and output maps produced for each of the three cases (the representative low, medium and high demand grids). A household (HH) density map is then assembled in ArcGIS, taking the Population

Density maps from the GPW V4 dataset [225]and dividing the raster by the average household size in the country or region of consideration to find the household density in HH/km^2 in the appropriate map format.

Each microgrid scenario (low, medium and high) have a differing number of paying customers used for modelling. The HH density raster is accordingly classified into four regions based on these customer quantity thresholds: below the HH density threshold; above the threshold for the low demand grid; above the threshold for the medium demand grid and above the threshold for the high demand grid. A categorised map is then used to assign the values for the low, medium and high results to each of the appropriate regions, resulting in a combined map with the results for each location dependent on the population density exhibited there.

The market potential in terms of population is found by calculating the sum of the population within the regions above the minigrid population thresholds, and subtracting from this population the number of people who would be better served by grid extension or the extension of existing infrastructure. The locations where this is assumed to be the case are identified through constructing a buffer around existing (and planned) grid lines [217], and combining this buffer with another buffer around areas exhibiting night time light pollution at levels above the average for cities in the region of consideration, assuming that night-time light emissions as observed by satellites correspond to artificial lighting, and therefore some degree of existing electrical infrastructure.

The buffer distance is chosen by comparing the price of grid extension per km with the Net Present Cost of the different architectures of the high, medium and low systems. A range of thresholds are calculated in HOMERPro for the different sizes of microgrids, and an average taken for all locations.

The financial market potential is calculated as the total investment (CAPEX) required to cover the electrification costs for all systems in areas within the population thresholds as described, and outside of the Grid and Lights Exclusion Zone. The total yearly operational expenditure for all systems is also found, in order to determine the yearly costs accrued by all systems. These outputs provide key metrics to inform the SMSE strategies, and serves as inputs for proceeding methodological steps.

3.6.5 Process: Mapping the solar microgrid ecosystem

Systems analysis of the microgrid sector reveals the necessary elements for a functional market, and identifies challenges, opportunities and activities that can lead to sustainable implementation of the technology. The purpose of conducting an ecosystem mapping exercise is to identify barriers preventing the widespread deployment of solar microgrids and provide recommendations for barrier removal to foster growth of the nascent sector.

In the Poor People's Energy Outlook, Practical Action defined the concept of an energy access ecosystem "*to describe the system conditions which could enable rapid growth in access to the range of energy services*" outlined in their minimum basic standards [140]. When analysing an ecosystem related to a particular technology and region (in this case, solar microgrids in the area or nation of interest) each of the influencing parameters affecting the viability of solar microgrids for rural electrification can be identified and evaluated in order to determine effective interventions for implementation and scale up.

With this in mind, the key output of this stage of the market assessment is to identify targeted interventions to strengthen the solar microgrid ecosystem and therefore the sustainability of solar microgrid systems. This is achieved by first developing an in depth understanding of the current state of the ecosystem and identifying any barriers that are inhibiting uptake and growth of the technology. The key is then to separate fundamental "uncontrollable" barriers (e.g., lack of solar resource) from more "controllable" barriers that can be overcome by targeted interventions (e.g., lack of local capacity to install and maintain solar microgrid infrastructure).

The final stage of this market assessment triangulates data found from the literature review through thematic coding [226]and structured analysis of identified themes. The key output of this section is a series of recommendations, designed to facilitate the transition to solar microgrid technological solutions recommended by the previous section. This is achieved through identifying the barriers preventing them from reaching scale and proposing targeted interventions to overcome them.

3.6.6 Market assessment outputs and feasibility check

Key market assessment outputs are market potential, site mapping and ecosystem barrier identification. These are used in proceeding steps of the methodology, along with outputs from the feasibility study for a defined use case, to conduct business modelling for scale up.

The primary feasibility check for this stage is whether there is an adequate market potential, with 'adequate' decided based on the envisioned scale of SMSE within the context it is modelled. A low market potential may occur due to a small number of sites, in turn due to high grid cover. One intervention to reduce this would be to confirm microgrid areas with the national grid operator. Further interventions can be made to reduce uncertainty of where the grid will go. A secondary feasibility indicator regards whether a favourable ecosystem is present. Eco-system mapping will highlight barriers stymying scale up of microgrid programmes. If any are identified as completely preventing microgrid deployment and inalterable then a negative feasibility is established until the barrier is removed. More likely, the analysis conducted will help to understand the nature and themes of the barriers, and inform recommendations to accelerate microgrid deployment through barrier removal, for example through policy advocacy, capacity building or supply chain development.

3.7 Business modelling for scale-up

The African Minigrid Development Association states that the largest indicator for reduced minigrid costs is shown by established developers in established markets, with experienced firms on average 41% less expensive than new developers in the same markets [56]. Accordingly, for microgrid developers to achieve sufficient cost savings to allow financial sustainability, operational strategies are needed at scale.

Based on outputs from the two preceding steps, further modelling investigates business growth scenarios for SMSEs, assessing the financial sustainability of SMSEs operating at scale by balancing costs of installing and operating microgrids with income from sales of electricity from a fleet of microgrids. The financial modelling broadly follows the steps outlined in section 3.5 to assess the feasibility for a single microgrid, but for multiple sites to investigate organisational cash flow forecasts and investment cases through different scenarios of deployment towards fulfilling the regional or national market potential identified in section 3.6. Inputs are taken from proceeding steps and complemented with up-to-date pilot data where available.

The determination of financial sustainability of a scaled SMSE is done so with consideration of the defining characteristics outlined in Section 2.3.2. For example, the increased costs of monitoring social impact and enhanced community engagement activities are also be factored into financial modelling, along with tariff considerations for ultra-poor community members.

3.7.1 Inputs: CAPEX and OPEX at scale

Implementing several microgrids over just one opens new economic models to be considered and new CAPEX costs to factor in financial planning. As microgrid companies grow they follow an experience curve whereby the upscaling of activities and outputs results in efficiency gains and cost reductions. For example economies of scale can be achieved through bulk purchasing of materials, as suppliers are able to offer discounts for increased volumes. In nascent markets where this methodology is aimed it is likely component costs for microgrids will be initially high, with costs falling over time as the market develops, more microgrids are installed and supply chains become stronger and more efficient. Even where high availability of solar PV modules, batteries and control equipment are available through an existing SHS market, specific components required for microgrid deployment such as smart meters, large inverters and distribution equipment will be expensive and difficult to obtain.

The primary input for this section will be the CAPEX costs obtained through section 3.5.9, with a discount applied to account for cost reductions through bulk purchasing. Assumptions for cost reductions achieved through bulk purchasing are context and time dependent, and as such the methodology is unable to offer specific guidance or rules of thumb. In order to gain initial values for cost reduction, suppliers must be consulted for quotes of varying volumes; alternatively, benchmarking studies offering regional benchmark prices for cost per connection, or costs for specific components are used as substitutes, with sensitivity explored during financial modelling. As more pilots are deployed, primary project CAPEX data are utilised.

Accurate OPEX costs of an SMSE operating at scale in a mature market are dynamic, being constantly updated as the business evolves. As the SMSE transitions to operate at scale, portfolio costs including managerial and technical staff salaries, as well as wider business costs including accounting, legal, and premises rental need to be considered. Operational and maintenance requirements of operating a fleet of microgrids will increase in total but reduce per microgrid as operational efficiencies are achieved. The management structures, staffing requirements and maintenance procedures for operating and managing a fleet of microgrids, and the associated impacts on microgrid finances, are the basis of current research [227] [228] and a highly complex problem dependant on geographical, economic and cultural conditions applicable to the region where the SMSE is operating. This problem becomes both an asset management and business planning conundrum, detailed analysis of which is deemed out of scope for this thesis.

Accordingly, the OPEX inputs for business modelling at scale start with the OPEX costs estimated in section 3.5.9, with sensitivity analysis conducted to explore cost reductions assuming operational efficiencies achieved through operating at scale. Once deployed, data from pilot projects including cost and frequency of maintenance trips, staff salaries, and cost and frequency of repairs are included as inputs for the modelling.

3.7.2 Inputs: Market potential and location

Parameters including number and locations of potential microgrids are provided directly from the market assessment outputs described in section 3.6. A selection of representative scale-up scenarios is analysed, accepting that SMSEs will not transition immediately from one microgrid to a national scale. The location of the microgrids identified through the market assessment is used for solar resource calculations in system design, while population density of regions identified for deployment are used for informing microgrid sizes, corroborated through site prospecting (Section 3.5.1).

3.7.3 Inputs: Demand and ability and willingness to pay

If resources allow, site surveys are conducted at selected sites to ascertain domestic demand and AWTP of prospective communities. The inclusion of PUE as an anchor load has a significant effect on microgrid finances, and specific PUE loads are also assessed during site prospecting exercises. For initial high-level assessment, demand estimations are used from the first use-case feasibility study (section 3.5.2), scaled for the number of households identified in the market assessment of the selected sites, with AWTP figures assumed to be constant across all sites. As primary data is collected through piloting, more accurate demand and measured AWTP data is aggregated and fed into the models.

3.7.4 Process: Site selection for fleet of microgrids over chosen region

Selection of specific sites to be included in the portfolio for analysis is guided from the market assessment outputs, located within regions identified as microgrids being the least cost electrification options. Further site prospecting surveys (Section 3.5.6) are completed to refine choices based on site selection scores and ranking. Proceeding steps are repeated for different scale-up scenarios representing different numbers of microgrids deployed, starting with microgrids located geographically close to reduce operational travel costs, scaling up to reach the desired market potential. The process is repeated iteratively with higher accuracy gained as more pilot data become available.

3.7.5 Process: system design of multiple sites

Load profiles of multiple sites are deduced from energy use surveys if available, otherwise determined through utilising the same assumptions for a single microgrid site in Section 3.5.2, acknowledging the application of one surveyed site to others may not have similar socio-economic and demographic conditions and will present uncertainty. Piloting provides primary data of measured load profiles reducing assumption uncertainty. System design including component sizing for multiple microgrid sites follows the same method as described in 3.5.7, using HOMERPro to design a least cost system using locally available components to cover the load profiles with the locally available solar resource. Each microgrid within the fleet is designed to supply its own load profile, with the geographical location input to HOMER to determine the site-specific solar resource for modelling.

3.7.6 Process: Financial modelling

To understand the financial sustainability and investment case of a SMSE operating at scale, financial modelling to determine a cash flow forecast and Internal Rate of Return (IRR) over the project lifetime is conducted, using input parameters from previous methodology steps. This is achieved through the

Odyssey tool, a financial model designed to help project developers and investors to evaluate the economic viability of mini-grid projects and portfolios at specific sites under local conditions before the project starts [178] .

Inputs for Odyssey include: system design and costs, number of customers and load profiles of multiple sites, tariffs, financing structure (debt, equity and grants), company overhead, tax, and other financial assumptions determined through of the proceeding sections of the methodology. The online tool allows the user to input these parameters, with a spreadsheet produced that allows for further inputs, outlined in Table 16.

Table 16: Odyssey Inputs

Theme	Input parameter	Notes
Demand	Load profile of different customer segments, number of customers in each customer segment for each site, expected growth rate (demand/number of customers)	Can be input from site prospecting assumptions, or use measured load data from pilot sites.
Tariffs	Avg. Connection Fee ($) Avg. Monthly Fixed Charge ($) Avg. Tariff ($/kWh	Disaggregated by Residential, Commercial and Public and if applicable, single phase and 3 phase
Operating Costs	Fuel Price ($) Metering Fees (% of revenues)	Metering fees applied to all revenues except connection fees
CAPEX costs	Solar PV, Solar Charge Controller / CCMPPT, Battery, Storage Inverter, Solar PV Inverter, Generator, distribution grid, house wiring, fixed capital costs	Include figures for Initial Unit Cost, Replacement Cost, Lifetime (yr) for calculating replacement and depreciation costs
Subsidy	Average % capex subsidy, Average subsidy per connection	If applicable
Financing	Project Start date, Discount Rate Capex Investment	Discount rate generally assumed 10% unless more accurate figure known
Grants and other Contributions	Village Contribution, Project Development Grant, Capex or Connection Grant Private Investment	Total Share (%)
Equity	Equity Investment, Predevelopment Cost, Total Equity Investment	If applicable
Debt	Amount of the Loan, Starting Year of the Loan, Loan Tenor [years], Interest Rate for Loan, Debt Grace Period [years], Transaction Costs Legal Fees Technical Fees	If applicable
Input for Balance Sheet, Cashflow, KPI calculations	Income Tax, VAT Regulator Tax, Other Tax, Communal Tax	If applicable
Portfolio Overhead costs	Salary Managing Director, Management and Technical Staff, Accounting, Travel and Vehicle Cost, Office costs, Company insurance, Other	$/Yr
Portfolio Development	Feasibility study, Environmental Impact Assessment, Generation / distribution license acquisition, Acquisition of capital incl. due diligence, Company foundation and establishment, Acquisition of land usage rights, Consultancy cost and fees, Set up of village and customer relationship	$ or $/yr

Odyssey uses the inputs provided to conduct standard cash flow forecasting by balancing income from electricity sales with operational and capital costs. Odyssey calculates annual depreciation of system components by dividing the upfront capital cost by the expected lifetime of the component, and summing for each component, including depreciation on system expansion if required. Options for grant, equity or debt financing can be explored. The financial parameters used in the model, with how they are calculated are outlined in Appendix 0 , which include Earnings before Interest, Tax and Depreciation (EBITDA), Earning before Interest and Tax (EBIT) and Earning before Tax (EBT), Net Profit, Net Present Value, Levelised cost of Energy, payback period and Internal Rate of Return (Levered and unlevered).

3.7.7 Business modelling for scale: outputs and feasibility check

The preceding steps are repeated iteratively to assess the financial sustainability of different scenarios of microgrid fleet deployments, increasing in accuracy as more pilot data becomes available. This analysis informs a business growth strategy for the SMSE and allows for a detailed plan to be presented to an investor or donor to finance the microgrid portfolio.

The ultimate goal of this section is a quantitative assessment of whether the SMSE modelled with the assumptions used throughout the methodology is financially sustainable over the proposed time period, at the scales proposed. The key financial feasibility check is determined by a positive portfolio IRR indicating there is an investment case for the portfolio, a payback period within the project lifetime, and a positive Cumulative Free Cash Flow to Equity some point over the project period. The Odyssey model outputs further economic key performance indicators such as total portfolio CAPEX cost, net profit, total revenue, LCoE, payback period, or Net Present Value, any of which can be used as a feasibility check depending on the investor or funder requirements that will be approached for financing the microgrid programme.

The financial performance outputs allow for detailed insight into the economic performance of a SMSE operating at scale, by investigating sensitivity analysis of certain parameters, insight can be gained on what is needed to increase sustainability, for example the quantification of a subsidy or reduction in operating costs. If the outputs suggest the SMSE operating at scale is not breaking even, the model offers insight as to why and the assumptions can be changed and the analysis repeated to determine what changes in the business model are needed to make the SMSE financially sustainable.

This section has outlined the methodology for assessing the financial sustainability of a SMSE, by conducting a feasibility study for a defined use case, assessing the market potential, and carrying out business modelling for scale up. The methodology indicates whether the SMSE fulfils the “Enterprise” part of its purpose. The next section looks at the “Social” aspect, by proposing a strategy for piloting solar microgrids, and setting out a methodology for assessing the performance and impact of a solar microgrid through a novel Key Performance Indicator framework.

3.8 Monitoring and evaluating the performance and impact a SMSE pilot using a Theory of Change and Key Performance Indicators

The outputs of the methodology outlined so far indicate whether an SMSE is financially sustainable at a specified scale in a given context and region, highlighting challenges and barriers to scaling microgrid operations. The logical next step is to implement a solar microgrid pilot project (or projects) to test the assumptions and gain a more detailed understanding of implementation and operation to inform further business modelling. The purpose of this section of the methodology is therefore twofold: to track the performance of piloted microgrids in technical, economic and social impact domains, and to gather primary data to use as inputs to repeat the feasibility assessment to yield more accurate outputs. Both have the objective of providing an evidence base for informing more sustainable solar microgrid business models and deployment.

This section begins by highlighting the need for holistic monitoring and evaluation of solar microgrids to inform business models, technical design and policy, before describing the theory of change and key performance indicator framework proposed. Data collection frameworks, data parameters to collect and analysis methods are then outlined, disaggregated between technical, economic and social data. The section concludes with an explanation of how pilot data is utilised through the KPI framework, and how these are tracked and subsequently used to inform business models and make recommendations in microgrid ecosystem.

3.8.1 The need for holistic monitoring and evaluation of solar microgrids to inform business models, technical design and policy

Accelerating solar microgrid deployment demands more than technical research, with effective energy planning methodologies needed for sustainable microgrid implementation. The success of solar microgrid operators depends on their ability to address the energy trilemma: security, affordability, and sustainability, all of which must incorporate social acceptance. Several projects have failed due to poor planning resulting in high energy costs that surpass the community's willingness to pay leading to reduced connections; oversizing due to inaccurate load growth calculations; failure to incorporate the microgrid into the local economy; inability to provide local support through the microgrid lifecycle; and failure to stimulate income-generating uses of electricity [24]–[26].

To address these issues and ensure the success of future microgrid projects, a whole system socio-techno-economic approach for solar microgrid project planning must be adopted, learning from the performance of existing microgrids through robust monitoring and evaluation frameworks. Performance monitoring has several benefits for multiple stakeholders in the microgrid sector. For developers, demand forecasting for current and future microgrids is improved, leading to more optimised system designs and lower capital costs; energy requirements and expansion options are better understood; and customer satisfaction surveys foster consumer confidence. Additionally, O&M expenses and system losses can be decreased, revenue collection can be raised, and technical system troubleshooting can be handled more effectively, improving system and supply reliability. Microgrid performance monitoring assists regulators and policy makers in determining precise short- and long-term energy requirements for a community or region, standardising system performance and services across developers, and documenting and verifying regulatory compliance. Finally, with developers better able to report and document business models, financial sustainability and returns, as well as improving understanding of risks and risk mitigation measures, investors and donors gain insight from performance tracking, enabling better targeted investment to unlock microgrid scaling [229]. High-quality integrated analysis tools utilising primary data can assist in microgrid project planning, but many monitoring frameworks focus on technical parameters and fail to incorporate economic or social aspects of the problem. Holistic planning tools and methodologies encompassing socio-economic impacts of microgrids on the local community to inform decision-making and enable the successful design and implementation of solar microgrids are required in order for them to scale sustainably.

It is acknowledged that measuring impact of energy access should go beyond the number of electricity connections and amount of energy consumed to also include quality of the energy service provided [230]. A growing body of literature highlights the limitations of the current binary indicators of energy access [231] [232] [233]. The ESMAP Multi-Tier Framework (MTF) [40]is frequently used to monitor progress toward SDG7, but has received criticism for failing to provide sufficient context for the nature of electrical connections and their effects on users [234]. The MTF is based on an underlying premise that increased energy consumption equates to increased welfare and wellbeing. Although energy has no intrinsic value, it is used to provide services that do, such as access to lighting, communication, entertainment, or the ability to run a business, which have inherent value to human wellbeing. Accordingly, using energy demand as a proxy for wellbeing from energy services is arguably crude [234]. A more sophisticated understanding of the social impacts of energy provision will allow for data-driven agenda development and policy formulation that recognises and addresses significant disparities in how well-equipped households use modern energy to maintain decent living standards. Definitions for social impact are many and varied [235], however it can be broadly described as the overall sustained outcome that an activity has on a community and the well-being of individuals and families [236], and can include both positive and negative effects.

Microgrids hold potential to contribute to several Sustainable Development Goals through fostering socio-economic development in rural areas by raising standards of welfare, education, health care, and technology [235] [237] [238]. Through the development of jobs, increased access to public services, and industrialisation made possible by stable and sustainable energy sources, addressing these issues enhances the quality of life in rural communities [140]. There is currently little documented evidence of the specific effects microgrid systems have on social infrastructure or general well-being of communities served, with reporting typically focusing on monitoring the technical and financial performance, often focusing on the financial rate of return on the initial investment associated with the deployed systems [238]. While measuring a project's social impact is acknowledged by stakeholders as a motivating factor, developers frequently do so insufficiently [238] and there is presently no common structure or set of metrics that developers may use to measure the rate of 'social' return on their investment [239]. Social Return on Investment (SROI) is well established in Social Enterprise economics as a method [240] for translating social value to monetary value and the SROI method has been applied to micro-hydro demonstrator projects [241] and solar energy solutions for schools and health centres in Kenya [242]. SROI is just one of many methods and frameworks designed to measure social impact [243], but all require careful design of what to measure and identification of appropriate indicators [244].

Measuring microgrid social impact alongside technical and economic performance enables transparent and holistic reporting on a project's overall performance, while identifying 'performance gaps' requiring additional support to improve the system's sustainability and impact [239]. Providing quantitative and qualitative data coupled with economic and technical information, offers a fuller more nuanced understanding of system performance, enabling evaluation of social value to be included and the impact of deployed microgrids to be maximised - improving future microgrid designs and business models.

This section therefore proposes a social impact focussed Key Performance Indicator framework for monitoring the impact and performance of a solar microgrid. The framework is set out and the process of selecting indicators for the framework aligned to a project's theory of change is outlined, with data collection processes and data analysis for the indicators suggested. The framework is utilised on a case study in Malawi in chapter 4.

3.8.2 Theory of Change

Microgrid performance and impact is measured through the implementation of a Theory of Change, shown in Figure 18, which specifies key changes an organisation or project wants to make, identifies all possible outcomes and outputs, and highlights activities that must be undertaken in order to achieve this goal [245]. Data collection informs progress toward outcomes: quantitative data analysis compares performance with targets to track and monitor project achievements and progress, and qualitative data analysis captures anecdotal and descriptive information used to provide feedback to system operators and stakeholders. Key Performance Indicators (KPIs) are quantitative or qualitative techniques used to compare components at each level of the Theory of Change, track the development of the activities involved, and evaluate the scope and pace of progress of a desired goal [239]. Used as part of a Monitoring, Evaluation and Learning strategy, they can track the performance of a microgrid in technical, economic and social realms. Literature on best practice for KPI frameworks utilised on mini and microgrids is common [139] [229], [246], [247]; however, most focus on technical and economic parameters. The KPI framework described here maintains that common techno-economic metrics used in the industry [229] [139] should be applied, but places more emphasis on applying metrics monitoring social impact that map to the SDGs.

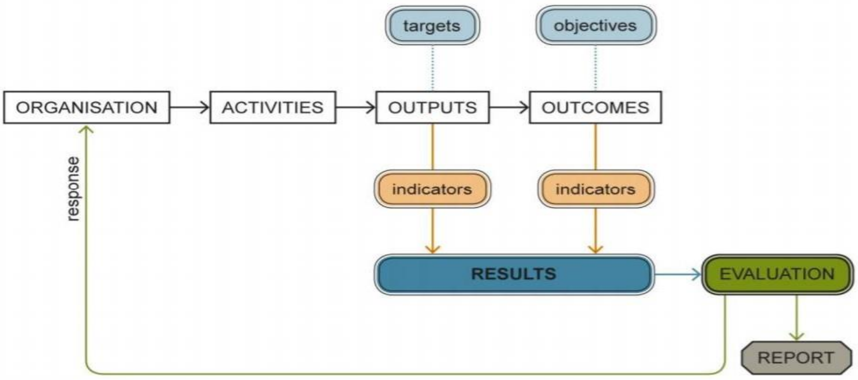

Figure 18 Block Diagram of Theory of Change [245]

3.8.3 Choosing Key Performance Indicators

The proposed framework does not attempt to provide an exhaustive list of all possible indicators that could be applied to any given microgrid development, instead the framework provides guiding principles that can be adapted on contextualised needs.

3.8.3.1 Technical Performance

Customer satisfaction and investor obligations are affected by number, length and frequency of power interruptions, and downtime has a direct impact on revenue generation. Tracking these metrics leads to enhanced methods for responding to technical issues causing microgrid outages.

Analysis of daily and seasonal generation and demand trends can identify supply and demand mismatches, which can be addressed through demand management. Assumptions in system component sizing can be tested through analysis of this data, and where necessary, these assumptions can be revised for future system designs, as well as monitoring PV degradation.

Demand in previously unconnected rural areas is uncertain, which can lead to microgrid oversizing and associated cost increases, or under sizing increasing risks of system failure. Analysis of daily battery state of charge, load profiles and monthly demand available from smart meter data for different customer segments can be used to test assumptions made in system component sizing, revealing and quantifying under and oversized generation or storage. Accurate analysis of load profiles and monthly demand from smart meter data for customer segments informs future microgrid designs to ensure optimum system size. Monitoring system demand segregated by customer segments (e.g. domestic, businesses, and institutions) enables trends identification and future demand predictions, informing tariff design and optimisation of system operation to improve customer satisfaction [6].

Understanding excess capacity enables appropriate business model interventions such as promoting daytime usage through lower daytime tariffs. Temperature measurements can be used to assess battery lifetime and aid troubleshooting.

The ratio of total useful energy consumed as a proportion of theoretically available energy is known as the utilisation rate, a typical KPI for a decentralised renewable energy system. Renewable Ninja [197] is used to calculate theoretical annual PV plant yield (in MWh/year) from inputs of generation plant GPS coordinates, generation capacity, system loss, and PV array tilt and azimuth. Annual demand available from smart meters is divided by the annual theoretical production to obtain the utilisation factor. This KPI is crucial to quantify how much energy is being wasted by the system, and can be used to inform demand side management interventions such as promoting daytime usage by lowering tariffs. It can also inform system sizing of future microgrids to reduce capital costs e.g. in the case of a low utilisation rate.

3.8.3.2 Economic Performance

Microgrid financial sustainability, direction of tariff modifications, and development of suitable business models for future microgrids all depend on understanding revenue generation. This allows a positive balance to be struck between income from electricity sales and operational costs for staff, maintenance and other running costs [81]. Analysis of electricity sales income also allows for detailed design of scaled operations where a portfolio of microgrids is deployed: the more revenue data available, the more detailed financial forecasts can be made [81]. Seasonal trends can be discovered through analysis of differences in the monthly microgrid income over the course of a particular year. Average Revenue Per User (ARPU) per month is a common metric used to evaluate financial performance, which is of particular interest to investors [248] . Monthly revenue totals for the entire microgrid are divided by the current number of consumers to determine ARPU. Customer segment disaggregated revenue measures revenue generated by different customer segments such as residential, productive users, and institutions informing business modelling. Such revenue data can be integrated into cash flow modelling providing precise income projections when new sites are chosen and surveys reveal a breakdown of consumer categories.

CAPEX and OPEX costs are recorded through efficient project record keeping and informs crucial economic KPIs including cost per connection, cost per kW installed and total cost of power. This allows comparison of microgrid economic performance to benchmarking, and offer essential metrics to share with donors and investors and use for business modelling at scale.

3.8.3.3 Social Impact data

Social impact indicators are framed under themes of Demographics, Energy Access, Health, Education and Communication, Employment & Finance, Woman Empowerment and Tariff & Service, linked to respective Sustainable Development Goals. Although monitoring these KPIs provides insight into changes happening within the microgrid community, direct attribution is not always possible due to the multiplicity of internal and external factors that affect local socio-economic development. A justification for the themes of social impact data indicators is provided below, while a comprehensive list of survey questions is outlined in Appendix 7.2.

- **Demographics:** Demographic questions seek to answer determine who the stakeholders that experience positive social outcomes are. This acknowledges that the impact created is greater if a particularly marginalised or underserved group of people is served.
- **Energy access (SDG7)** Understanding microgrids contribution to national SDG7 targets includes tracking number of customers, with potential unconnected customers as a number and percentage also tracked. Tracking numbers of energy consuming devices and methods of lighting tracks community progress away from traditional energy use such as candles, torches and kerosene to more sustainable solutions higher up the energy ladder. Satisfaction with energy access is also tracked. Monitoring how the microgrid affects local cooking practices can also be incorporated, however solar microgrids generally don’t power electric cooking devices apart from some small-scale pilots [249].
- **Health, education and communication (SDG 3,4,9):** Lack of access to basic services like safe drinking water, a healthy diet, and primary healthcare services links poverty to poor health. Inadequate access to healthcare and proper sanitation increases the likelihood of death from preventable diseases, and inadequate access to healthcare for women limits access to family planning information, raising fertility rates in underdeveloped nations [250]. Microgrids can offer positive impacts on health and monitoring health-related metrics enables understanding on health impacts and associated improvements in quality of life [142], [237]. Access to health information increases awareness and understanding of common illnesses and diseases, and enables informed decision making to prevent them. KPIs tracking access to health centres, access to health information, and reduction in burns injuries (for microgrids offering eCook) tracks health impact related to the microgrid.

Education is fundamental for growth, productivity, and development within communities; it is foundational for family welfare; and it provides people with essential political knowledge [251]. Education can also create employment opportunities and raise income levels and improves the individual mental health capacity, thereby improving their decision-making capabilities and reasoning skills [246]. Education KPIs track number of schools connected, number of schools with ICT, children attending school, and number of children studying in the house due to microgrid electricity. Further qualitative monitoring can be conducted through informal interviews with head teachers to ascertain microgrid impact on school learners, or tracking pass rates, although the latter is difficult to attribute directly to the microgrid.

Literature suggests that access to information and digital communication contributes to increased social and economic development [252]. [253] states that access to information and communication contributes to development in the broadest sense as well as the expansion of human freedoms, while [254] posits that information is not only a source of knowledge, but also a source of advancement of economic, social, political, and cultural freedoms, and that access to and use of information and communications are essential conditions for development. Accordingly, KPIs tracking microgrid impact on communication and information ask questions regarding access to local and international news, as well as mobile phone ownership and use, disaggregated by smart phones. Additional questions ask who uses phones, and what they are used for.

- **Employment & finance (SDG 8):** Economic growth generates job opportunities and hence stronger demand for labour, the main and often sole asset of the poor. In turn, increasing employment has been crucial in delivering higher growth [133]. [255] states that “Increasing employment and ensuring decent work for all are essential aspects of sustainable development. Quality employment and decent work conditions help reduce inequalities and poverty, and empower people, especially women, young people and the most vulnerable such as people with disabilities”. Thus, employment enables income generation and is critical to increasing living standards, purchasing power and affordability of basic needs. Gathering data on employment and finance enables understanding on the economic impact the microgrid has on individual households and the community as a whole. Understanding whether customers have had an increase/decrease in household income and expenditure is also essential to informing tariffs and business models
- **Female empowerment (SDG 10):** Microgrids have the potential to contribute to SDG10, to achieve gender equality and empower all women and girls [256]. It has been shown that women can benefit significantly from having a reliable access to energy, through use of

appliances for cooking, lighting and entertainment, as well as offering routes to emancipation and empowerment, through releasing them from long hours of household work through engaging in income generating activities within the home and community [257]. Studies have shown that electricity access can be 'gendered', providing men and women with different opportunities and benefits from electricity access [258]. Female run businesses enable economic and social power for women to move out of poverty, readdresses the unequal gender attitudes that women often experience; and opens opportunities [259]. Female empowerment indicators track number of women with access to electricity and number of female owned businesses, as well as female customer perception of the microgrids impact on their lives.

- **Tariff & Service (SDG 9):** [260] recommends gathering customer experience data to provide valuable insights for companies to inform sales and business performance, stating that such data often correlates positively with social impact. Accordingly, indicators related to tariff and service monitor customer satisfaction with the cost and method of purchasing electricity. Monitoring how much customers pay against how much they would like to pay, allows tariff adjustments to ensure affordability. Additional questions explore whether electricity payments are a burden, or if spending is cut back on other areas.

3.8.4 Data collection

Informative, useful and holistic insight on microgrid performance demands a variety of quantitative and qualitative data collected through multiple methods including remote monitoring, smart meters and surveys. Economic and technological performance monitoring conducted in conjunction with suitable social impact quantification allows cross analysis of both social impact and technological performance to fully determine the success of a microgrid project. This section outlines the available tools and methods for collection of technical, economic and social impact data.

3.8.4.1 Smart metering

Smart metres, connected to a utility company's database via a gateway of communication interface protocol, serve as a home's interface between the smart grid and the rest of the home's electrical demands in the context of a smart grid [261]. Smart meters designed exclusively for solar microgrids provide real-time data on a variety of factors, such as revenue generation, demand, frequency of payments, and connection status. Data is typically accessible by an API, spreadsheet downloads, or an online user interface.

3.8.4.2 Remote monitoring

Remote monitoring refers to the observation of a remote (often off-grid) energy system from a distance. The majority of currently available remote monitoring systems (RMS) track functionality and performance of energy generation systems, and provide technical assistance for system operators by making it easier to conduct maintenance tasks in remote areas. They also enable sustainability evaluation of off-grid renewable energy systems after the project is finished [262]. Similar to smart meters, most RMS provide data download through customised web portals.

3.8.4.3 Surveys

Through face-to-face surveys with microgrid customers, trained enumerators utilising smart phones collect precise qualitative and quantitative data. Survey quality is improved through the use of both male and female enumerators, appropriate survey questions to prevent survey bias, and keeping the survey short [239]. A baseline survey conducted during pre-installation phase gives a complete picture of a community's demographics, energy use, and quality of life, with subsequent follow-up surveys conducted periodically to track impact, ideally every six months.

3.8.4.4 Focus Group Discussions

A focus group discussion involves gathering people from similar backgrounds or experiences together to discuss a specific topic of interest. It is a form of qualitative research where questions are asked about their perceptions, attitudes, beliefs, opinion or ideas [263]. The purpose of a focus group discussions is to determine, through participatory methods, qualitative input regarding the microgrid, and can be used alongside surveys to provide further insight on microgrid social impact.

3.8.4.5 Project management documentation

Valuable qualitative and quantitative data is obtained through project management implementation records, in the form of meeting minutes, budgeting spreadsheets, invoice repositories, and project diaries. Effective training of fieldwork staff ensures records kept are accurate and up to date and should form part of effective capacity building processes within a SMSE. The data gathered through these methods provides insight into CAPEX, OPEX and field experiences outlined below, used primarily as inputs to the economic viability methodology steps rather than KPI tracking.

3.8.5 Using KPI data to track SMSE performance and inform business models/ecosystem for improved sustainability

Having outlined the motivations for collecting and analysing pilot data, the methods and tools for data collection and the data parameters to collect, this section explains how the data is used to increase the sustainability and scale of implementation of solar microgrids, specifically through utilisation of a

KPI framework, informing business models, and making recommendations to inform the microgrid ecosystem.

3.8.5.1 Field experiences

The purpose of this step is to highlight qualitative lessons learned through firsthand microgrid implementation experience. It highlights unforeseen challenges in microgrid implementation that cannot be accounted for through prior desk study and informs future deployment. Field experience data arises from project management documentation and informal interviews with project developers and field staff, drawing out key lessons learned during the microgrid implementation, documented in order to increase efficiency, speed and cost reductions of future installations.

3.8.5.2 Tracking microgrid performance using the KPI framework

A full list of Key Performance Indicators to monitor microgrid performance proposed by the methodology is presented in Appendix 7.3 (with specific KPIs used in the case study highlighted). The list includes industry standard indicators, taken from NREL Quality Assurance Framework for Minigrids [139], as well as further social impact indicators explained in Section 3.8.3.3. The proposed list is not comprehensive, but designed to provide a wide selection of potential indicators, allowing microgrid developers to tailor their list according to their programme theory of Change, which will include obligations to funders or investors.

In order to use the KPI frameworks, a dashboard is created which contains columns for planned versus actual performance against each of the indicators at certain milestones, used to track the overall performance of a microgrid over time. Targets are set and performance against the targets tracked over time, shown in Table 17.

Table 17: Tracking KPIs over time

Indicator	**Units**		**Baseline [Date]**	**Milestone 1 [Date]**	**Milestone 2 [Date]**	**Milestone 3 [Date]**	**Final target [Date]**
Indicator 1	units	Planned					
		Current					
Indicator 2	units	Planned					
		Current					
Indicator 3	units	Planned					
		Current					

Parameterised indicators are used to measure project performance and value for money (or cost efficiency), assessing the costs incurred against performance/outputs achieved. This is done by tracking project/programme spend against indicator actuals, but the indicators used can vary. Economic or business indicators such as number of connected customers, peak generating capacity, annual revenue or peak demand are often used as the proxy for project progress, with costs accordingly parametrised in units i.e. \$/MW, \$/connection and \$/kWh.

3.8.5.3 Informing SMSE business models

Microgrid profitability relies on strong understanding of the end-users and their economic and cultural contexts, which is difficult and requires significant time and resources. Regular monitoring and evaluation of end-users and their interactions with energy systems is key, enabling adaptation and tailoring over time. A few examples of areas with high potential for optimisation include tariff structures and levels, customer engagement strategy, incentive structures for demand stimulation and changes in technical design to better reflect use patterns.

All of the above optimisations rely on inferring the causality between technical design and performance to social and economic impacts, for example linking the impact of implementing new customer training to customer drop-out rates. Regular data collection of planned versus actual performance across multiple metrics enables accurate analyses of such relationships (provided that organisations/businesses carefully tailor their indicators to the questions and causality they want to assess). This will increase the certainty with which optimisations can be designed and implemented.

By comparing KPI data with delivery model approaches, insight is thus used to determine the effect different delivery models have on the social impact. This analysis is then used to determine the extent to which solar microgrids impact socially on the communities they serve and form recommendations to inform SMSE business models interventions, such as capacity building, community engagement, or appliance financing schemes, or gender based interventions. For example, setting tariffs that allow customers to pay for electricity for a period of time in advance to ensure that they have a sufficient level of electricity throughout the year could be introduced. This would be aimed at customers who typically struggle to maintain a sufficient level of household income during more difficult times such as droughts, or lean seasons. The impact of these additional interventions can be tracked through the KPI framework, with a data set available to inform the benefit of the additional costs and the impact on the overall business model.

3.8.5.4 Informing recommendations in the microgrid ecosystem

Technical, economic and social impact data is useful for many broad stakeholder groups, including: Governments, to inform subsidies, policy and regulatory changes; Investors, for de-risking investments, promoting awareness and justifying social impact motivations; and Donors, to apply for and report against grant/concessional funding and to demonstrate beneficiary impact.

Exactly which of these functions is relevant and how will be different for different organisations, depending on their delivery model and what indicators they choose to track. In all cases it is beneficial for the sector if there is greater data being collected and made available (even if anonymously), which can be used to inform the decisions of the above stakeholder groups.

Microgrids require a supportive policy environment and subsidies to scale and operate sustainably. Many governments now recognise, at least in part, that mini and microgrids can be economically viable solutions for certain remote communities, but a number of concerns and misunderstandings remain. Microgrids are frequently perceived as providing a subpar service when compared to grid power [63], or that they are only owned and installed by international companies using international equipment. To secure long-term government support for mini-grids through policy changes and subsidies, it is necessary to persuade governments that microgrids meet their socioeconomic development objectives and that enough value is created and retained within the country itself (including job creation). These factors require supporting evidence, and given a lack of this evidence currently, support is likely to be readily available to those developers that can demonstrate strong socio-economic impact and value creation. Specifically, KPI data collected allows a cost benefit, or social return on investment for microgrids operated through a social enterprise framework to be quantified, and compared with other forms of rural electrifications. This has significant implications for informing electrification policy decisions.

The lack of demonstrated successful business models and precedents means that most investors perceive microgrids as high risk. Perceived returns or those returns able to be evidenced are not sufficient to bear the perceived risks for investors, limited by low ability to pay and demand. The IFC concluded that “there is a dearth of data-driven analysis of the operational and financial performance of the sector” and “limited insight into what constitutes a financially sound business” [25]. This is arguably the main factor limiting the scale of microgrids businesses globally. Increased access to data on the financial, technical and socio-economic performance of successful microgrids is essential to unlock sufficient volume and combinations of capital flow to projects at the critical points in their life cycles. Reported KPI data thus reduces perceived risk to investors by quantifying performance and impact, leading to increased investment and deployment of microgrids.

3.8.5.5 Refining assessment of SMSE feasibility through re-iteration of methodology with updated input data

Having outlined recommendations for what data to collect through pilot projects, Table 18 outlines where pilot data can be used as inputs to repeat the methodology. The inputs highlighted in bold are taken from pilot data to repeat the processes to produce updated outputs and feasibility checks with greater accuracy; the method of data retrieval (smart meters, remote monitoring, surveys or project documentation) is given for each. As more data are collected the process can be repeated in an iterative manner, increasing the utility and accuracy of the methodology with each iteration.

Table 18 Pilot data used as inputs for methodology

Inputs	Processes	Outputs	Feasibility Check
1. Feasibility for a defined use case			
Site prospecting data **Load Profiles (SM)** Solar Resource **Local component Costs (PD)** **Ability and Willingness to Pay (SM,S)**	Site Selection System Design Tariff Calculation Financial modelling	CAPEX OPEX Cost Reflective Tariff Cash Flow Forecast	Cost Reflective Tariff vs Ability and Willingness to Pay Local Supplier Availability Single microgrid economically viable
2. Market assessment at a regional or national scale			
CAPEX (PD) **OPEX (PD)** **Load Profiles (SM)** Geospatial data Competitor technology costs	Techno-economic modelling Geospatial modelling Ecosystem Mapping	Market Potential and deployment cost Site Mapping Ecosystem Barrier identification	Adequate Market Potential Cost competitive deployment against competitor technologies Favourable Ecosystem
3. Business modelling at scale			
CAPEX at Scale (PD) **OPEX at Scale (PD)** Market Potential **Multiple site load profiles (SM)**	Site selection for fleet of microgrids System design of multiple sites Cash Flow forecasting at scale	Scale up scenarios Detailed Financial planning and business model Operational strategies	Scaled operations economically viable

3.9 Chapter Summary

This chapter has proposed a detailed methodology for assessing the feasibility of solar microgrid social enterprise in a given country or region. The methodology can be used as a planning tool for microgrid practitioners, researchers or decision makers to accurately map the processes involved in designing and implementing a microgrid business.

The first section of the methodology assesses economic viability of the SMSE through a feasibility study of a defined use case, allowing analysis on a site level to provide key outputs necessary for scaling up, and shows the technical feasibility of comparing ability and willingness to pay against the cost reflective tariff. A market assessment then takes the outputs of a single site feasibility and examines a region or national scale to explore how the market potential of microgrid customers. It offers an indication of how many microgrids could be installed, what the costs would be and high level geographical and economic indicators of the feasibility of the social enterprise operating at scale. The final section of the financial sustainability of the microgrid business operating at scale, examines cash flow forecasting and ultimate economic viability of the enterprise.

The second element of the methodology explores the social impact of microgrids, through a novel Key Performance Indicator framework to track impact on health, education, access to energy and economic development of the microgrid programme. These two methods are then tested through piloting microgrids and gathering data. This data is then utilised to better understand the performance of the microgrids, and key data is inserted as inputs to the methodology to be repeated in an iterative way. Through this iterative process, the methodology is honed, and outputs from the methodology used to inform key decisions to improve the sustainability of the microgrid enterprise.

Having presented the anatomy of the methodology, the following chapter demonstrates the application of the methodology on a real-life use case of a pilot solar microgrid project operating as a social enterprise in Malawi. This application of the methodology has allowed a degree of validation of the methodology’s efficacy and usefulness to stakeholders, and highlighted opportunities for its refinement and improvement.

4 Validation of methodology: Use case in Malawi

The purpose of this chapter is to test and validate the methodology proposed in Chapter 3 through describing its application in a use case, namely assessing the feasibility of a SMSE in Malawi. In doing so, assumptions and efficacy of the proposed methodological processes are tested. Use case primary data derives from an active solar microgrid project conducted by the University of Strathclyde and United Purpose Malawi from 2018 – 2023, providing significant insight into the feasibility of SMSE in Malawi and recommendations for scaling.

The chapter begins by providing relevant context regarding Malawi and its energy access sector, with an overview of the Malawian microgrid sector, current and potential roles microgrids have in achieving SDG7, and an introduction to the project under which the case study microgrid has been implemented and primary data collected. The proceeding sections follow the methodology steps proposed in chapter 3, namely assessing the financial sustainability of a SMSE by conducting a use case feasibility study, carrying out a market assessment and conducting business modelling for scale-up, and utilising the KPI framework to assess the impact and performance of a pilot microgrid. Feasibility checks and targeted recommendations are given in each section, while wider conclusions on the feasibility of an SMSE in Malawi, and a critical assessment of the value and efficacy of the methodology are provided in a discussion in Chapter 5.

4.1 Energy access and solar microgrids in Malawi

4.1.1 Overview of the Malawi energy sector

Malawi is a small, landlocked country in Southern Africa covering 118,484 km and home to an estimated population of 18.6 million (2019) expected to double by 2038 [264] with about 80% of the population living in rural areas [265]. Malawi is one of the poorest countries in the world, with the formal economy in the country producing a Gross Domestic Product (GDP) per capita of approximately USD 399, largely through agricultural production which accounts for 30–40% of GDP and employs approximately 80% of the country's workforce [266], making the country particularly vulnerable to erratic rainfall and unpredictable weather caused by climate change. In 2020 Malawi's poverty rate using the international poverty line of USD 1.90 per person per day was 70.8% [267], Income inequality remains high with an estimated GINI coefficient of 44.7 in 2016 [268] and it ranks 109 out of 183 in the ease of doing business index for 2019 [269], indicating challenges for international business cooperation. Malawi has one of the lowest electrification rates in the world, with overall access at 18% overall, with grid electricity contributing 11.4% while off grid solar PV accounting for the remaining 6.6% [270]. The access rate for rural areas is even lower at 4%. Therefore, about 14.4 million people in Malawi have no electricity, and those with grid access regularly experience blackouts and brownouts.

Malawi has an installed capacity of 532 MW, comprising hydroelectric (372 MW), Biomass (18.5 MW) and diesel and other generation (141.5 MW) and a recently installed 60 MW Solar PV plant [271]. There are currently no interconnections to neighbouring country grids of Mozambique and Zambia. 99% of hydropower resources come from the Shire river and supply 80% of the country's power needs, with diesel generators used mainly for emergency or stand-by generation [272]. The reliance on hydropower and especially on one river makes Malawi highly vulnerable to changing rain patterns, siltation and flooding of the power plants, exacerbated by climate change and deforestation along the Shire catchment areas. The grid-connected installed capacity is already insufficient to meet peak demand, with a deficit expected of 1,748 MW in 2026 and 2,408 MW by 2030 [154]. Generation capacity deficit coupled with climatic impacts reducing hydro output result in significant load shedding being experienced throughout the country, exacerbated by recent critical infrastructure damage caused by tropical storms [274].

The Integrated Resource Plan (IRP) for Malawi [275] reviewed and updated previous load forecasts for Malawi and prepared an inventory of local energy sources and potential power generation projects. The modelling predicts that both generation and transmission capacity need to be expanded significantly to meet future demand requirement, and that additional generation will be met mainly through new hydro and coal generation, with small contributions from fuel oil and renewable energy plants. Malawi has 400 MW of coal under development with the National Energy Policy stating that the government will "encourage the private sector to take a leading role in the coal industry subject to regulatory and licensing requirements" [276]. Moves towards coal power generation within the context of a global climate emergency have been criticised, with the Climate Policy Initiative stating that such investment presents a misalignment with a net zero economy and the falling costs of renewable energy technologies [277].

The Government of Malawi has responded to these challenges by publishing a National Energy Policy in 2018 [276] and National Renewable Energy Strategy in 2017 [278] as well as implementing comprehensive power sector reforms. he Malawi Rural Electrification Programme (MAREP) fund has been used primarily for grid extension, connecting the national grid to 435 trading centres by 2015 [153], with minimal government efforts on off-grid solutions until recently, stymying overall access to electricity in the country.

4.1.2 Distributed solar PV in Malawi

According to the IEA, distributed and renewable solutions (specifically solar PV) are seen as essential to achieving energy for all by 2030 in Malawi [27]. Supported by reductions in technology costs in recent years, Solar PV solutions including PSP, kiosks, and microgrids are proving feasible for meeting lower tier electricity needs [40] [279] and are the focus of most off-grid energy projects, with the county's off-grid PV installed capacity (including PSP, SHS and mini-grid) increasing from 0.2 MW in 2007 to 10.4 MW in 2016 [280].

In 2012 there were an estimated 7,000 PV systems present in the country, though many are known by practitioners not to be fully functional [13]. A market assessment for off grid technologies found that PV systems have a significant role to play in the electrification of off-grid communities in Malawi, that PV is scalable across the entire country and its modularity and simplicity are ideally matched to the needs of off-grid communities, where technical capacity and individual household demand is low [14] . Rural energy projects in Malawi typically include aspects of community ownership and operation and target a public facility such as a primary school or health centre [152]. Despite providing high short-term social impact, several projects have fallen short of sustainability expectations, typical of the historical experience with off-grid renewable energy projects in SSA [128]. Project sustainability of off-grid programs in Malawi has remained an ongoing issue for practitioners; evident in the number of installed solar PV systems in Malawi that fall into disrepair well before their expected lifetimes. There appear to be few case studies of sustainable rural energy business models in Malawi with adequate capacity to operate and maintain the systems and the collection of tariffs enabling cost recovery of capital investment within a reasonable timeframe, as well as operation and maintenance costs.

4.1.3 Mini-grids as a key energy delivery model for Malawi

There is a growing consensus on the role of community mini-grids in Malawi to complement the currently overwhelmed national utility power supply via ESCOM. Malawi has set the target to electrify 80% rural population and reach universal modern energy access by 2030 and is exploring both on-grid and off-grid solutions [276]. Mini-grids have already been recognized as a key part of a portfolio of interventions to improve electrification rates, particularly in areas that will not be reached by the national grid in the near future. Accordingly, the Government of Malawi has set a target of 50 mini-grid systems to be in place by 2025 [278]. The context for and expected contribution from renewable energy mini-grids is reflected in several key policy and planning documents [276]. While there may be further enhancements possible, the overall legal framework in the country adequately allows for the planning, development, operation, maintenance and utilization of mini-grids in Malawi. The addition of a Mini-grid Regulatory Framework, published mid 2020 after extensive consultation, created a firm foundation for mini-grid development as well as private sector participation in developing this sector [281].

Mini-grids present a significant opportunity to both enhance energy access and promote private sector participation in energy delivery in Malawi. However, there is a lack of valid evidence in terms of impact regarding mini-grids in Malawi. The country has seen a number of mini-grid pilot installations, including very small projects, containerized systems, community led projects and hydro mini-grid projects. Over the years, there have been several case studies, many failures and lessons learnt which have contributed to the emerging sector. Past failures have mainly been ascribed to (i) lack of funding for sustained operations and maintenance of systems, (ii) quality of equipment or installations and (iii) limited community ownership [17]. A Summary of past and present mini-grids in Malawi is summarised in Appendix 7.4.

Considering the evidence presented above, solar microgrids hold potential to offer a low carbon cost effective pathway for Malawi to achieve SDG7, offering a viable, fast and sustainable rural electrification option, and an alternative to reduce the requirement for grid expansion and associated coal generation.

4.1.4 EASE solar microgrid project

The Rural Energy Access through Social Enterprise and Decentralisation (EASE) project [282] focuses primarily on SDG7 progress in Malawi and runs from October 2018 to March 2024 with funding from the Scottish Government. EASE is coordinated by the University of Strathclyde (UoS) with collaborating partners United Purpose (UP), Community Energy Malawi and WASHTED. EASE aims to increase access to sustainable energy for rural communities in Dedza and Balaka, thereby enabling economic development and improved livelihoods. A primary output of the EASE project is to install two solar microgrids in Dedza district, generating and distributing power for localised domestic and productive use of rural villages. The motivation for the project is to pilot and demonstrate a social enterprise ownership model for solar microgrids in Malawi, and to use this project as a platform to expand microgrid deployment across Malawi. The application of the methodology and primary data collected from the EASE microgrid project forms the basis for the use case in this thesis.

4.2 Prerequisit activities for Malawi

4.2.1 High level assessment of solar microgrid feasibility in Malawi

The proposed high-level screening indicators as proposed in Chapter 3 are specified with Malawi's indicators stated in Table 19. Malawi fulfils the pre-requisite checks of being a low-income country, low electrification rate and low number of active microgrid installation.

Table 19 High Level suitability screening for Malawi

High Level Screening Indicator	Malawi Value
Low-Income countries in Sub-Saharan Africa, defined by the World Bank, as nations that have a per capita gross national income (GNI) of less than $1,026	Malawi on World Bank Low Income country list, GNI: $580 in 2020 [283]
countries with a low access to electricity rate (<30%) according to world bank data [190]	Malawi access to energy in 2019 11.2% [4]
early stage or nascent microgrids sectors, and only countries should be considered where very few microgrids have been deployed (suggested as <20)	Active number of Microgrids in Malawi: 11

4.2.2 Learning from existing initiatives

In order to inform the methodology, three microgrid projects were evaluated through fieldwork visits and expert interviews with project developers in 2017, a summary of the key features differentiating the existing initiatives used to inform the methodology in Table 20. Each initiative is then summarised, with key findings used to inform the methodology highlighted.

Table 20. Comparison of key features for each initiative considered.

Initiative Parameter	**MeshPower** [15]	**Steamaco** [16]	**SoNG Project** [6**2]**
Country	Rwanda	Kenya	Kenya
PV Array Size	1 kW	5 kW	3 kW
AC/DC	DC	AC	DC
Number of Customers	20	50	
Energy End Use	Lights, phone charging	Variety of domestic and productive uses	Portable Battery Kits, On site productive use
Business Model	Fee for Service	Pre pay per kWh	Various
Payment method	Mobile Money	Mobile Money	Mobile Money
Ownership	Offices in UK and Rwanda	Offices in UK and Kenya	Academic Pilot, Village Energy Committee

4.2.2.1 Steamaco

Steamaco was founded in 2012 as the fall of global prices accelerated the spread of solar PV in Kenya and decentralised mini-grids gained traction globally as a rural electrification strategy. An identified market gap was noted in methods to collect and enforce payments for power: smart meters were identified as a viable solution and this gap in the market became the organisational focus. Ten pilot microgrids utilising the Steamaco-developed Bitharvester remote payment platform were installed across Kenya with impact investment funding, one of which was visited for this research. Steamaco are now operating globally, with their main income from the supply of their Bitharvester product to minigrid operators.

4.2.2.2 MeshPower

MeshPower [15] formed in 2012 from a student society at Imperial College, UK, initially testing solar PV kiosks and portable battery kits rental in Rwanda. Realising the potential market, the team decided to venture into the rural electrification sector, specifically in minigrids. The MeshPower Microgrid product was developed to provide DC power to rural communities in Rwanda with support funds from a partner investor. Following substantial growth, MeshPower at the time of fieldwork had 3 managers and 24 in-country staff operating 78 grids across Rwanda, each with between 12 to 50 customers per grid, a total of 1,859 customers.

4.2.2.3 Solar NanoGrid (SoNG) project

The SoNG project [285] coordinated by Loughborough University has been designed as an inter-disciplinary project bringing together social scientists and engineers to work together to pilot a novel technique for rural electrification in Kenya and Bangladesh. Four specific communities were identified in the target countries for microgrid projects to be installed, which was followed by extensive consultation within the chosen communities, design of the system and agreement over the business model to be employed. The installation and operation of the microgrids themselves was followed by a two-year process of observation and evaluation. The case study evaluated for this paper was in Nakuru County, Kenya.

4.2.2.4 Key lessons used to inform the Malawian microgrid design

- **Flexible tariffs**: Creating flexibility of payments such as a kWh tariff, time dependent tariffs, or flat rate tariffs, increases system affordability for customers. PAYG payments enable business customers to avoiding overpayment and reduces the entry barrier for energy use, thus enabling more responsive and robust businesses. MeshPower promote “fee for service” model, whereby customers are billed per hour of service they receive (rather than per kW), with services including phone charging, LED lights and DC TVs.
- **Remote monitoring:** Preventative maintenance can be conducted through the remote monitoring meaning that instead of travelling, problems can be diagnosed and solved in the office, saving on time and costs.

- **Importance of data:** All initiatives highlighted the importance of data capture and analysis to inform technical design, operation and maintenance, troubleshooting, billing and tariff design, and business models.
- **Employ a site agent:** All initiatives employ local staff to conduct preventative maintenance including PV module cleaning, distribution line inspection and battery maintenance. They also act as an interface between the customers and operator, recruiting new customers and discuss tariff options with customers.
- **Use Pay As You go (PAYG) payment methods:** Payments are made via local mobile money platform as a per kWh prepayment with payment transactions sent logged on smart meters. Some systems allow customers to pay an onsite agent with cash. Pre-payment reduces risk of default payments, and helps customers track their energy spend.
- **Promote productive uses of energy to stimulate demand:** All initiatives noted the need to increase demand leading to increased revenues, however acknowledging this can be challenging in communities with subsistence-based economies. PUE such as salons, welders, grocery shops, and video halls were indicated as viable local businesses that increase microgrid demand.
- **Use smart meters**: All initiatives highlighted the importance of enabling of remote payments, low balance reminder functionality, and remote switching when balanced run out.
- **Community consultation:** All initiatives engaged target communities to identify key priorities and specific desired services and productive uses in the community. This was followed by a system design and costing exercise, testing the community ability and willingness to pay and checking for any technical constraints.

4.3 Feasibility study for defined use case in Malawi

The methodology steps outlined in Section 3.5 were followed to conduct a feasibility of a single microgrid in the Dedza district of Malawi. Input data is utilised primarily from the pilot project described in more detail in Section 4.6, with outputs gained for use in proceeding methodology steps.

4.3.1 Inputs: site prospecting data

The site selection process followed the fieldwork guidelines outlined in Section 3.5.1, and utilised data gained from a literature review, including a review of the Dedza Socio-economic profile [286] to find statistics on a Traditional Authority (TA) level on indicators relating to site selection criteria, shown in Table 21. Green cells indicate high suitability based on specified criteria, suggesting priority TAs to be Kachindamoto, Kachere, and Kaphuka.

Table 21 Traditional Authority Level on indicators relating to site selection criteria

Site selection Criteria	Location	Productivity	Payment for services	Payment for services	Local Capacity	Payment for services	Security	Potential consumers	Security
Indicator	**Population**	**youth population**	**number of skilled people**	**Number of trained teachers**	**No of CBOs**	**Number of COMSIP* Groups**	**No of community Protection centres**	**Number of Health facilities (total)**	**Number of child offenders**
Kachindamoto	93808	28870	5007	322	19	368	169	41	1
Kachere (Pemba)	131840	41550	7140	428	54	486	378	44	5
Kaphuka	134459	41861	7215	410	29	851	313	38	3
Kasumbu	71128	22508	4764	410	33	322	141	37	7
Chilikumwendo	60961	18257	3376	179	36	320	169	35	4
Tambala	62107	18918	3359	146	19	652	327	32	3
Chauma	20874	6383	1326	61	10	172	129	14	1
Kamenyagwaza	28237	10112	1891	115	20	384	70	35	3

4.3.2 Inputs: Energy use surveys and load profiles

Data collection was carried out in August 2016, a summary of the sample sizes, estimated population and associated degree of uncertainty is outlined in Table 22.

Table 22 Demand Survey Sample Sizes

Survey	Sample Size	Estimated Population	Confidence Level	Margin of Error
Household	90	186	95%	7.5%
Business	27	27	99%	1%

Load profiles for different customer segments were modelled based on existing and aspirational energy use of the village taken from the demand survey analysis. The calculated load profiles were compared to measured load profiles from equivalent solar microgrids in existing literature for validation. Table 23 shows the assumptions made to calculate total hourly demand for the microgrid for one customer segments, with the full assumptions provided in Appendix 7.6 and the final modelled load profiles used for generation system design represented graphically in Figure 19.

Table 23: Daily Energy for example Customer Segment

Household - low income						
Appliance	**rating (W)**	**Time ON**	**Time Off**	**hours/day**	**# Appliances**	**Daily Energy (Wh)**
Lights	5	18:00	21:00	3.00	4	60
Radio	5	18:00	21:00	3.00	1	15
Phone charging	5	18:00	19:00	1.00	1	5
					Total	**80**

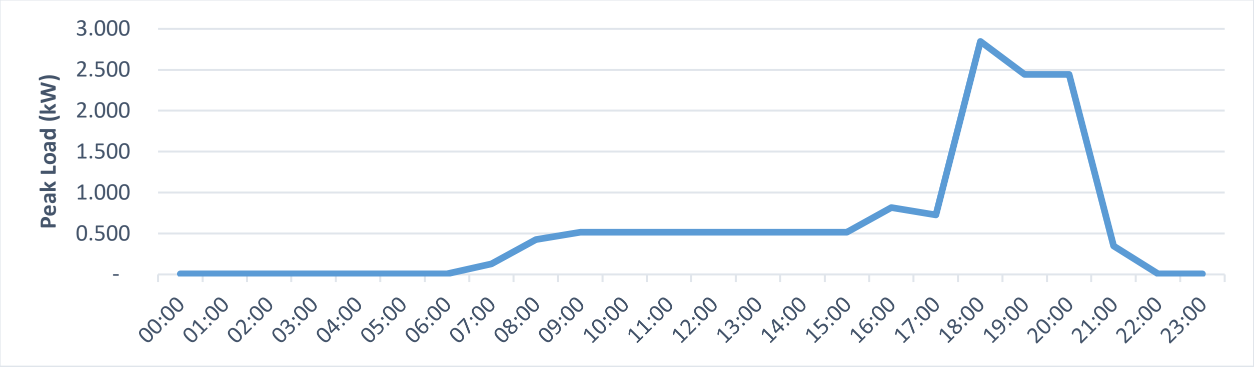

Figure 19 Microgrid Demand

4.3.3 Inputs: solar resource

The latitude and longitude measurements for the selected site were input as -14.247403333333333 34.607020000000006, the resulting seasonal average daily radiation and clearness index from HOMERPro is shown in Figure 20. A scaled annual average of 5.33 kWh/m^2/day was used, with low and high sensitivities of 5.02 kWh/m^2/day and 6.42 kWh/m^2/day respectively used to investigate seasonal variation in solar resource.

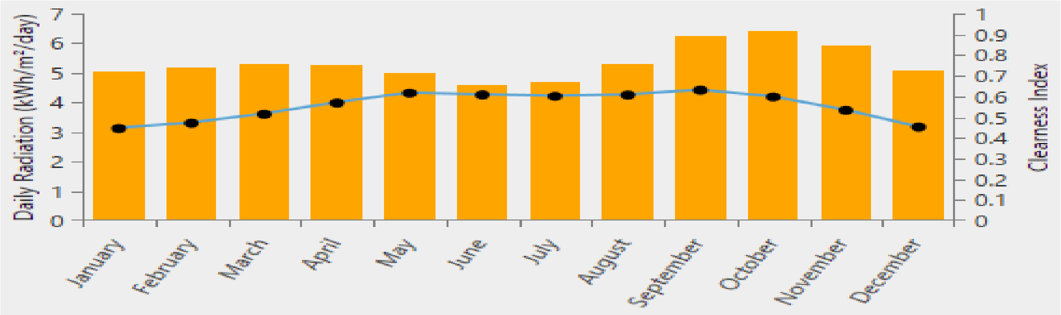

Figure 20 seasonal average daily radiation and clearness index

Temperature sensitivity values were taken from the same HOMERPro NASA data set and are shown in Figure 21. Scaled annual average taken as 22.42^{0}C, with low and high sensitivities of 18.95^{0}C and 25.9^{0}C respectively used for the analysis.

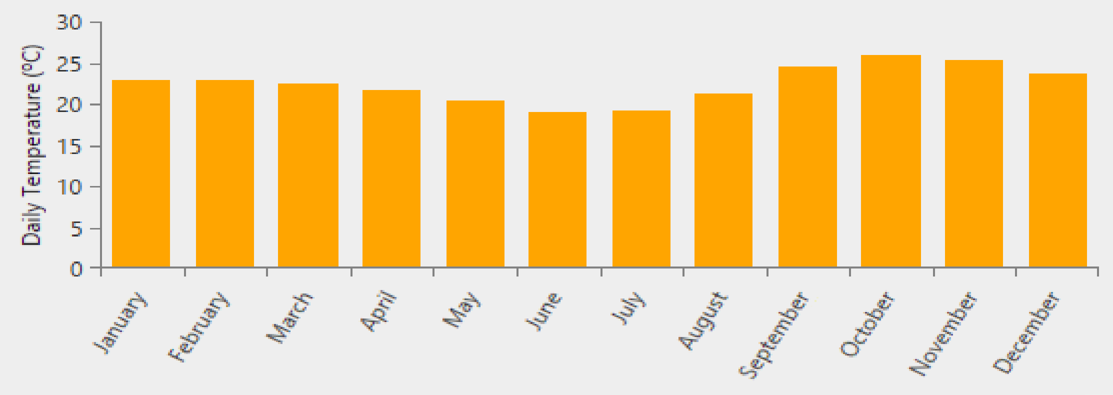

Figure 21 Seasonal average temperature variation at chosen site

4.3.4 Inputs: Local component cost and OPEX costs

A procurement process was undertaken to get quotes from local suppliers for solar PV equipment, distribution equipment, batteries and axillary equipment including installation costs, involving a Request for Qualification followed by a Request for Proposals. The prices received outlined in Figure 22 were significantly variable, reflecting a nascent market with unexperienced suppliers and perceived risk reflected in high costs. Component costs and operational costs used for the modelling were taken from as purchased pilot costs and measured pilot operational costs, summarised in 4.3.7.3. OPEX costs are summarised in Table 24.

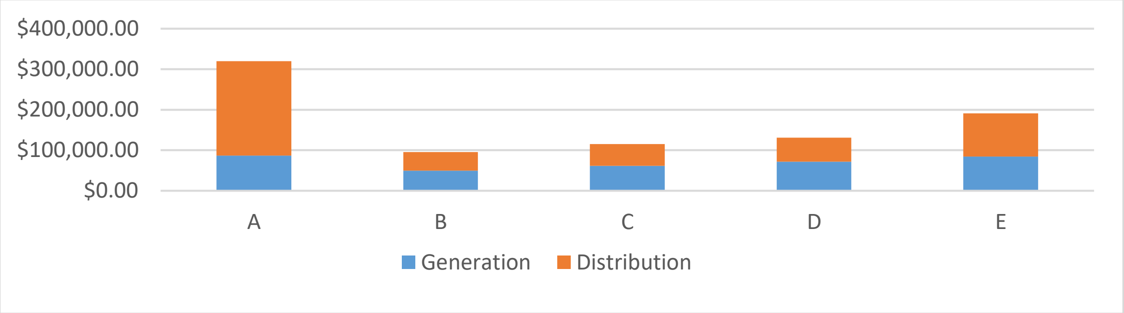

Figure 22 Procurement responses (USD)

Table 24: OPEX costs

OPEX component	Month (USD)	Annual (USD)
Data for 3G router (16,800 MWK per month)	20.16	241.92
Steamaco SaaS Fee 0.54 USD per meter	32.4	388.8
Steamaco SMS fees (average)	23.84	286.08
Site agents – (2 x 50,000 MWK per month)	120	1440
Security Guard (50,000/m)	60	720
Generation and Distribution Maintenance (600,000 MWK per year)	60	720
TOTAL SITE BASED OPEX COSTS	*316.4*	*3796.8*

4.3.5 Inputs: Ability and Willingness to pay

Several indicators for AWTP based on demand surveys and project baselining studies were determined. Key indicators including monthly income, current monthly energy spend and the results of the direct questions on how much respondents would be willing to pay for certain services are shown in Table 25.

Table 25: Household and Business Mean AWTP

ATP Indicator	Monthly spend (MWK)	USD
Household AWTP		
Average household monthly income	20,000	24.38
Monthly Energy Spend	3,648	4.38
Monthly Dry Cell Plus Mobile spend	2,228	2.67
Household WTP for lighting and phone charging	5,689	6.83
Business AWTP		
Average business monthly income	160,000	192.02
Monthly Business WTP for lights and phone charging	7,415	8.90
Monthly Business WTP for a business connection	10,611	12.73

4.3.6 Process: Site selection

11 villages were surveyed, 3 were excluded following conversations with Dedza DEC indicating they were soon be electrified by the grid (Chiothera, Chakachadza, Mphathi). The survey results translated into normalised scores for each indicator are summarised in Table 26. The joint winners were found to be Mthembanji and Kafere, following a conversations with the site enumerators, Mthembanji was chosen as the site.

Table 26 Site selection scores

	Kudembe	**Sitolo GVH**	**Mthembanji**	**Ndindi**	**Che Jero**	**Kafere**	**Tsoyo**	**Tambala**
Distance to grid	0.8	0.8	0.4	0.6	1	0.4	0.4	0.4
Request for grid put in	0.6	0.6	1	1	1	1	1	1
market held in village	1	0	1	1	0	1	1	1
market frequency	0.6	0	0.6	1	0	0.6	0.6	0.6
population density	0.6	0.6	0.6	0.6	0.4	0.6	0.6	0.4
distance between the houses	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
number of houses	0.2	0.8	0.2	0.4	0.4	0.6	0.2	1
Grocery Shops:	1	0.4	0.6	0.4	0.2	0.6	0.4	0.4
Restaurants:	0.2	0	0.2	0	0	0.8	0	0
Liquor Stores:	0.2	0.4	0.6	0	0	0.4	0.6	0
Building Material Shops:	0	0	0	0	0	0	0	0
Wood/Metal workshops:	0.6	1	0.4	0.6	0.6	0.6	0.2	0.8
Barber Shops:	1	0.2	0.6	0.6	1	1	0.6	0.6
Phone Charging:	1	0.8	1	1	1	1	0.8	0.6
Maize Mill:	0.6	0.2	0.6	0.2	0.4	1	0.2	0.6
Tailors:	0.8	0.4	1	0.8	0.6	0.6	0.2	1
Other:	0.2	0	0.6	0	1	0.2	1	0
diesel generator powered businesses	0.6	0.6	0.2	0.6	1	0.2	0.2	0.2
institutional energy use	0.4	0.4	0.4	0.4	0.4	0.2	0.6	0.4
road quality	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.4
village accessibility	0.6	0.4	0.6	0.6	0.6	0.6	0.4	0.6
Productive uses	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2
Corrugated Iron roofs	0.4	0.6	0.6	0.6	0.6	0.6	0.4	1
Theft occurrences	0.8	0.2	0.8	1	0.2	0.4	0.2	0.6
CBO presence	0.2	0	0.2	0.2	0.2	0.2	0	0.2
VSL	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mobile Signal	0.4	0.6	0.8	0.6	0.6	0.4	0.8	0.6
	14.4	**10.6**	**14.6**	**13.8**	**12.8**	**14.6**	**11.8**	**13.4**

Mthembanji is located in Katchindamoto Traditional Authority in Dedza district, relatively close to Lake Malawi (Figure 23). It has an estimated 186 households and 27 businesses and is unlikely to receive a mains grid connection in the near future. The main forms of economic activity in the village are rice farming, agribusiness, grocery shops and video shows.

Figure 23: Location of Mthembanji (Map Source Google Maps)

4.3.7 Process: system design and cost

4.3.7.1 Generation design

Load profiles by customer segment, comprising the results of energy use surveys described in Section 4.3.2 with added calculated internal load for smart meter base demand and air conditioning used for modelling is shown in Figure 24. Utilising prior inputs comprising load profile (4.3.2), solar resource (4.3.3), and local component costs (4.3.4), HOMERPro output a cost optimal system to fulfil the load requirements. The system diagram with key component costs is shown in Figure 25.

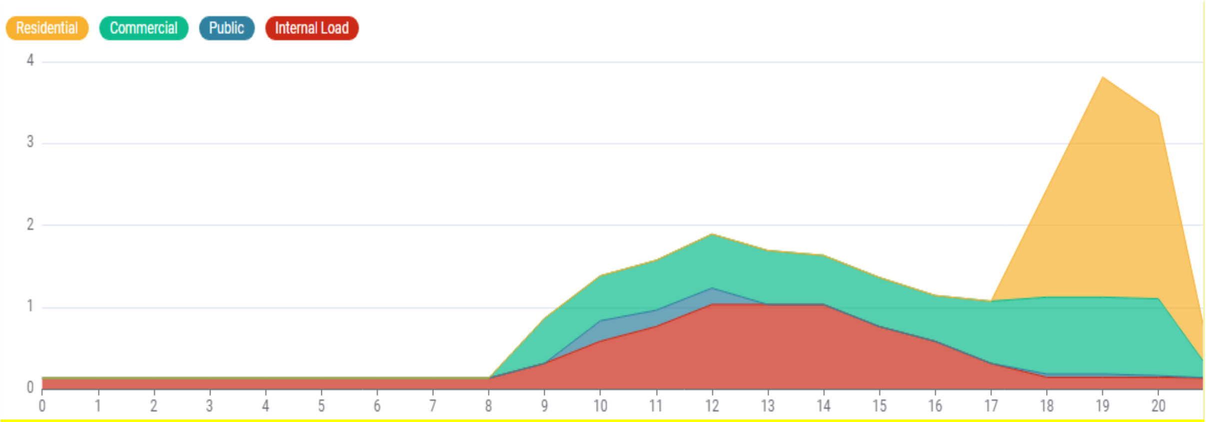

Figure 24 Load profile by customer segment

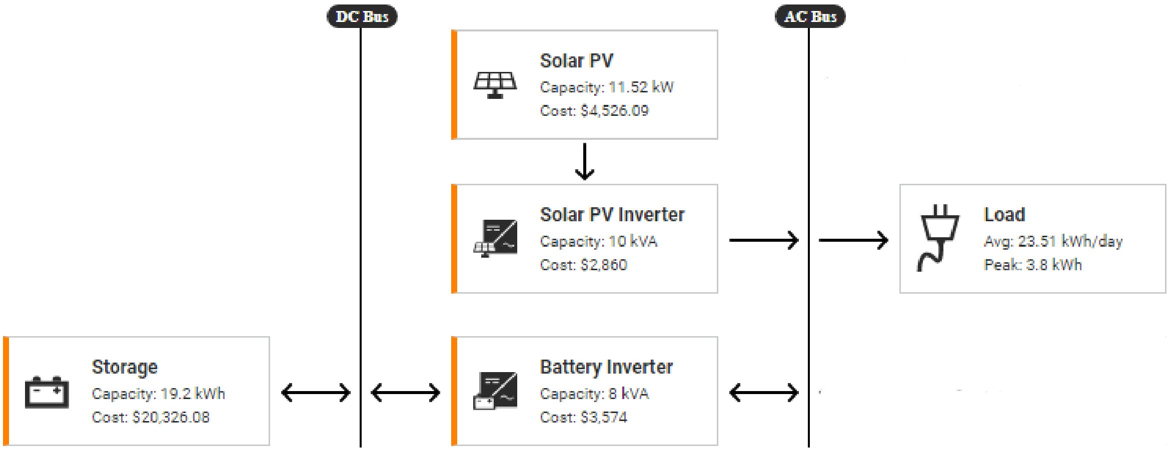

Figure 25 Generation system as designed

4.3.7.2 Distribution Design

GPS coordinates of customers were recorded during site surveying, including locations of households, businesses, generation site, obstacles (including trees or vegetation noted by the enumerators that might interfere with the distribution grid) and roads (GPS coordinates taken at intervals along important roads in the village). The distribution grid is designed to link to the central generation site, with 240V radial distribution lines following roads in the village, with poles positioned at 50m spans. From poles supply lines connect customer houses, utilising Overhead Aluminium Aerial Bundled Cables with 9m wooden poles. Choosing overhead cables make installation less costly avoiding costs for digging trenches, and makes crossing roads more straight forwards. Customer GPS coordinates are shown in Figure 26. All coordinates lie within a 600m radius of the central generation site to prevent excess voltage drop at end of line. GPS coordinates were used with the clustering and least path connection algorithm described in section 3.5.7 to position and connect distribution poles, and determine length of cable required displayed in Figure 27 , allowing a bill of quantities with costs to be produced.

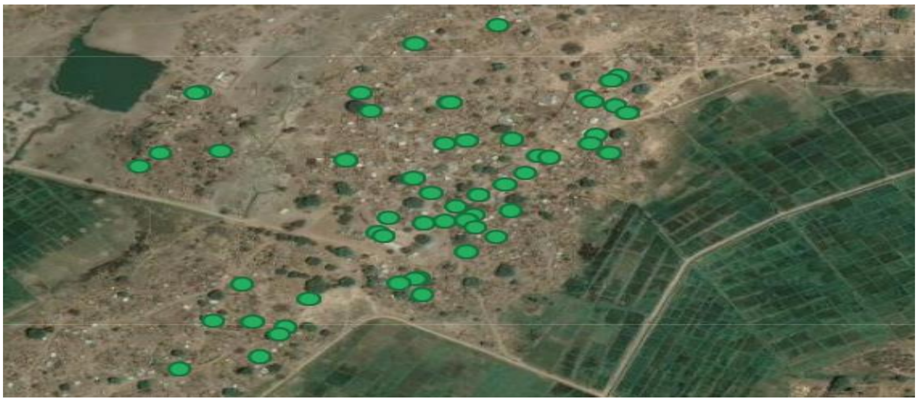

Figure 26 Customer locations

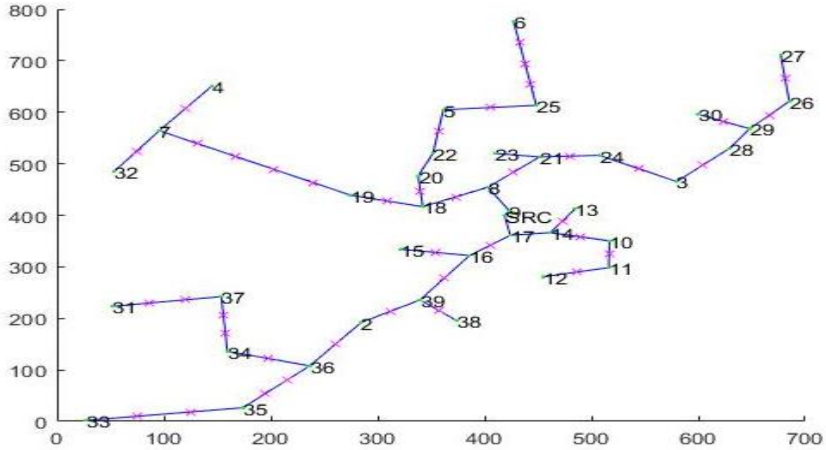

Figure 27: Least path algorithm results

4.3.7.3 CAPEX

CAPEX costs including generation, distribution and smart meters, installation and fees are taken from pilot installation costs and summarised in Table 27. Not included in these costs are development costs, including staff time for site prospecting, community engagement, fieldwork and technical design and project management, which are included in business modelling for scale up.

Table 27 CAPEX costs for a single microgrid

CAPEX Item	Cost (USD)
Generation	55,603
Distribution and smart meters	27,968
Installation and fees	18,425
Total	101,995
Cost per connection	1,700
Cost per kW	8,869

4.3.8 Process: Cost reflective tariff calculation

Using the inputs above and calculation described in 3.5.8 a Cost Reflective Tariff (CRT) is outlined for the first 5 years Table 28. The CRT for the first 5 years is calculated as USD 0.72/kWh, while the average tariff over 20 years, including inflation and expected demand increase is USD 0.91/kWh. These figures have been compared to the ability and willingness to pay of the communities, by converting WTP figures from Table 25 in Section 4.3.5 to USD/kWh, and presented in Figure 28.

Table 28 Cost reflective tariff calculation steps

Year	1	2	3	4	5
Total revenue requirement (Site Operating costs) ($)	3796	4,024	4,265	4,521	4,792
Billed consumption (kWh)	5,583	5,750	5,923	6,101	6,284
5 year NPV (revenue requirement) ($)	21,398				
5 year NPV (billed consumption) (kWh)	29,641				
Starting Cost Reflective Tariff without levies ($/kWh)	0.72				
Average Cost Reflective Tariff over 20 years ($/kWh)	0.91				

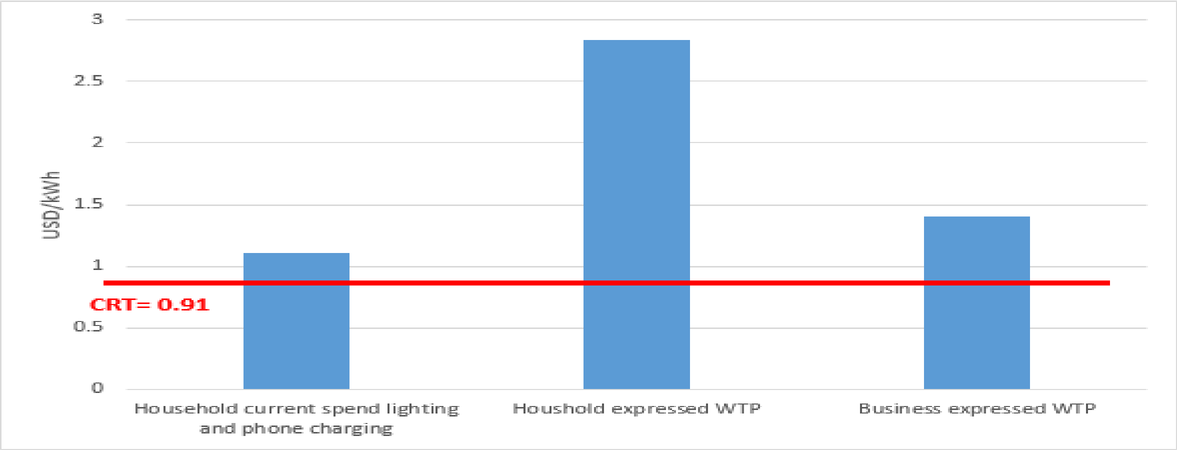

Figure 28 CRT comparison with AWTP

4.3.9 Feasibility for a defined use case: Outputs, Feasibility Check and Discussion

4.3.9.1 Outputs:

The feasibility study for a single microgrid has produced key outputs of CAPEX (USD 101,995) and annual site based OPEX ($3,796.8). These CAPEX and OPEX outputs are used as a basis for inputs for proceeding sections of the methodology. Similarly, the load profiles, component costs and HOMERPro models form a basis for subsequent modelling and can be updated as more pilot project data become available.

4.3.9.2 Feasibility Check

Comparing the CRT to customer ability and willingness to pay has also proved to be positive, with the CRT lower than the current household energy spend on mobile charging and dry cell batteries. The CRT is used to form tariff bundles and discussed in more detail in Sections 4.5 and 4.6. The feasibility check of availability of local suppliers was also shown to be positive, although only just. The high variation in procurement quotes suggests an adversity to risk with few suppliers having installed a solar microgrid before reflected in high costs. The first step of the methodology suggests that a single solar microgrid is feasible with the assumptions provided, with outputs provided to conduct the proceeding steps of the methodology.

4.3.9.3 Discussion

The first section of the methodology is primarily used to produce outputs for subsequent steps. The above processes are repeated for any microgrid considered in a portfolio, and accuracy is increased as further primary data is gained through piloting. Specifically, load estimations increase in accuracy as pilot data allows for specific customer segment load profiles to be compared with detailed energy use surveys. Additionally, uncertainty in local component costs can be reduced as up to date CAPEX costs for recently installed microgrids, averaged over several installations, are utilised.

Detailed cash flow forecasting is not conducted at this stage, as this is examined for multiple sites where wider business costs for an SMSE can be included in portfolio modelling. The high-level feasibility check of CRT with AWTP gives an indication of how income will balance with expenditure and is essential for designing tariff bundles in business modelling for scale-up. For Mthembanji, the expressed WTP for electricity is higher than the CRT. This willingness is supported by customer estimates of their affordability, although these estimates may be higher than what is actually feasible, especially given the seasonal nature of incomes in rural areas. The estimates give an indication that cost reflective tariffs can be affordable, an assumption that is then tested through piloting.

4.4 Market assessment of solar microgrids in Malawi

The market assessment presented in this section follows the steps outlined in Section 3.6, and utilises data from an early high-level feasibility study of a solar microgrid in Malawi [191]. The preceding feasibility study for a defined use case, and the proceeding business modelling at scale section, utilise primary cost data from the pilot microgrid described in Section 4.6, as this is more relevant in informing Malawi specific results. Ideally, all sections would use concurrent and unified data, but due to the nature of implementation and availability of field data gathered this wasn't possible. The validation of the market assessment steps of the methodology presented here provide utility and value, but should be repeated with up to date data to increase accuracy, detailed in recommendations in Chapter 5.

4.4.1 Techno-economic inputs

The market assessment for solar microgrids in Malawi compares LCoE of microgrids with diesel generators and national grid extension at a national scale across Malawi. Input data on microgrid costs, performance and useful delivered energy has been input from a prior microgrid feasibility study [191] including load profiles, component costs, and business operational, management and administrative costs.

Three models were designed, broadly based on findings of the feasibility study and arbitrarily adjusted to explore different sized microgrids catering for high, medium and low demand levels, at 4.14 kWh, 10.65 kWh and 24.18 kWh daily energy consumption respectively. Cost curves were built in HOMERPro for key components based on quotes collected in [191] which allow HOMERPro to optimise the system designs based on resource and cost inputs. A summary of the data utilised for the three models used in this study is shown in Table 29, while the costs associated with generation and storage units used for the modelling are given in Table 30.

Table 29: Key Data for modelling and mapping for each micro-grid size

	Small Grid	**Medium Grid**	**Large Grid**
Number of customers	30	54	70
CAPEX per customer ($)	827.97	789.78	1,068.87
OPEX per customer ($/year)	53.20	48.76	56.34
Average Daily Demand	4.14 kWh	10.65 kWh	24.18kWh
Battery Specification	6V 240 Ah Victron AGM Lead Acid Batteries		
Battery Capacity (kWh)	11.52	34.56	57.6
PV Specification	Monocrystalline 250W 30.49V 8.2 A Isc = 8.78 Voc = 38V Jink/JA		
PV Array Size	2	4.5	10
Inverter size (kVA)	2	4	8

Table 30 Cost data for generation and storage units

Component	**Size**	**Capital ($)**	**Replacement ($)**
PV Unit	2kW	3,234	1,600
PV Unit	4.5kW	5,978	4,970
PV Unit	10kW	13,137	8,000
Battery	2.89 kWh	651	651
Gen-set	1kW	122.4	122.4

4.4.2 Geospatial inputs

In this study, four geographically varying factors were considered to define each location within Malawi: Solar Scaled Average (kWh/m^2/day), Scaled Average Temperature (^{o}C), Diesel Fuel Price ($/L) and System O&M trip cost ($/year). Table 31 shows the input values for the diesel price mapping process, while the assumptions and values specific to Malawi for the geospatial maintenance costs, are outlined in Table 32. Technician wages and lodging costs were taken from correspondence with United Purpose Malawi.

Table 31 Assumptions used for inputs into Fuel Price Modelling

Variable	**Description**	**Assumed Value**
P_d	Pump price of diesel	890.9 MK/L [55]
c	Average diesel consumption rate of fuel delivery vehicle	8 L/h
t	Travel time from diesel pump to site	Calculated from accessibility mapping
v	Volume Capacity of Diesel Fuel per transport vehicle	30 L
N/A	USD to MK exchange rate	1 MK = 0.0014 USD

Table 32 Assumptions used for inputs into maintenance costs

Variable	**Description**	**Assumed Value**
N_{Tech}	Number of Technicians visiting site (inc. drive)	2
W_{Tech}	Maintenance Technician Hourly Wage	10,000MK[1]
t_{maint}	Maintenance time	4 hours
C_{lodge}	Lodging Cost per Technician Per Night	30,000MK[1]
t_{day}	Number of days spent on maintenance trip (rounded down) to indicate number of nights of lodging required	Calculated from accessibility mapping
$C_{Overhead}$	Overhead cost associated with system administration.	Dependent on system size

4.4.3 Ecosystem mapping inputs

The ecosystem has been mapped using available relevant literature and previous project case studies relating to energy access, solar PV and minigrid projects in Malawi over the last 10 years [288] [289] [290] [155] [217] [153] [291] [151]. Regulatory frameworks relevant to ecosystem mapping were found from relevant institutions including Malawi Energy Regulatory Agency (MERA) [292] [281] and the Government of Malawi Department of Energy Affairs [276] [278]. Appendix 7.7 provides further details.

4.4.4 Process: Quantifying the market through techno-economic modelling

The Household (HH) density raster, classified into regions based on customer quantity thresholds for each size of microgrid (outlined in Table 29) is shown in Figure 29, a categorised map used to assign the values for the low, medium and high results to each of the appropriate regions. This resulted in a combined map with the results for each location dependent on the population density exhibited there. Figure 30 shows the exclusion zone defining the area of Malawi not considered for microgrid implementation on the basis that these areas are best served by existing infrastructure.The exclusion zone used was developed by constructing a 2km buffer around existing (and planned) grid lines in Malawi [217], and combining this buffer with another 2km buffer around areas exhibiting night time light pollution at levels above the average for cities in Malawi. The buffer distance of 2km was chosen by comparing the price of grid extension per km with the Net Present Cost of the different architectures of the high, medium and low systems, resulting in a range of thresholds varying from 0.86 km to 3.21 km, with the intermediate value of 2km used for all locations.

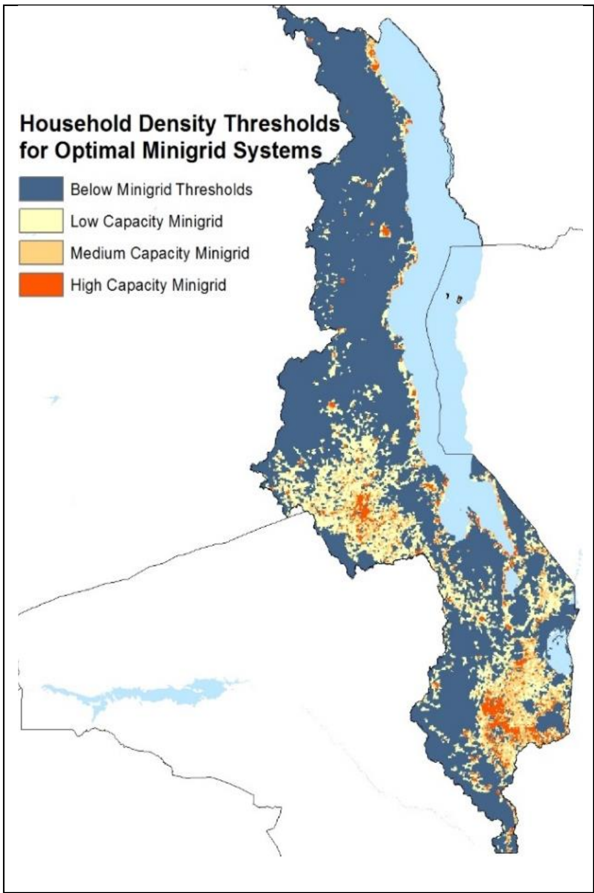

Figure 29 Optimal Micro-grid size by location, based on Population Density data [225]

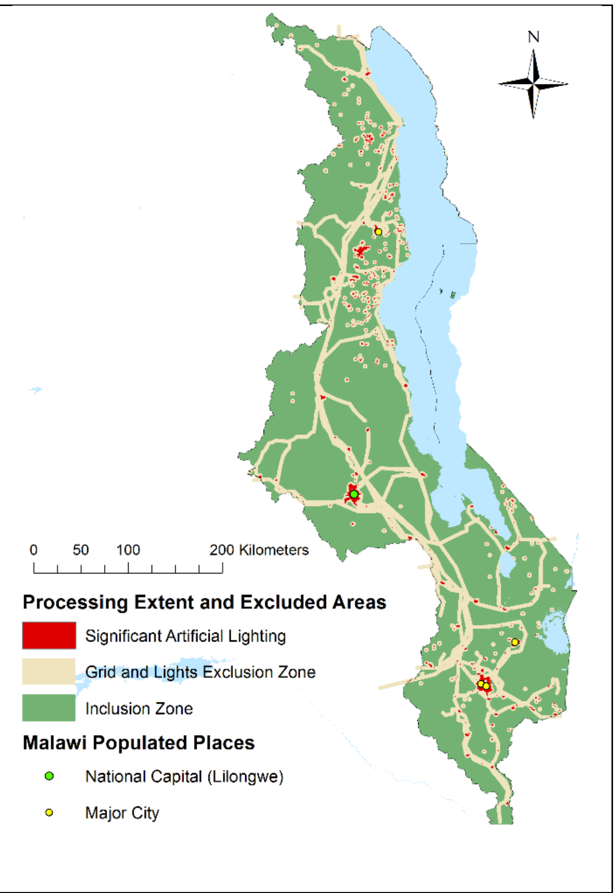

Figure 30 The inclusion and Exclusion areas based on Night time Light Pollution, Existing and Planned Grid Infrastructure and a 2km buffer around features

Figure 31 and Figure 32 show the Cost of Energy in $/kWh for the optimal system at each location for solar PV and diesel microgrids respectively. From these maps it can be seen that more accessible locations (closer to cities and towns) exhibit lower LCoE, which is due to the need for larger systems in these locations along with the lower cost of maintenance visits and in the case of the diesel microgrids the lower cost of diesel fuel. In every location within the inclusion zone the LCoE for a solar microgrid was less than a diesel microgrid in the same location, with improvement of solar microgrid LCoE over diesel microgrid LCoE ranging from 0.03 $/kWh to 1.19 $/kWh. Diesel microgrids are most competitive (i.e. the savings are the least) in locations where the demand/population is relatively low, but the fuel cost is also low due to proximity to nearby diesel pumps. Conversely, solar microgrids present the greatest value proposition where demand is high, or in locations far from fuel pumps.

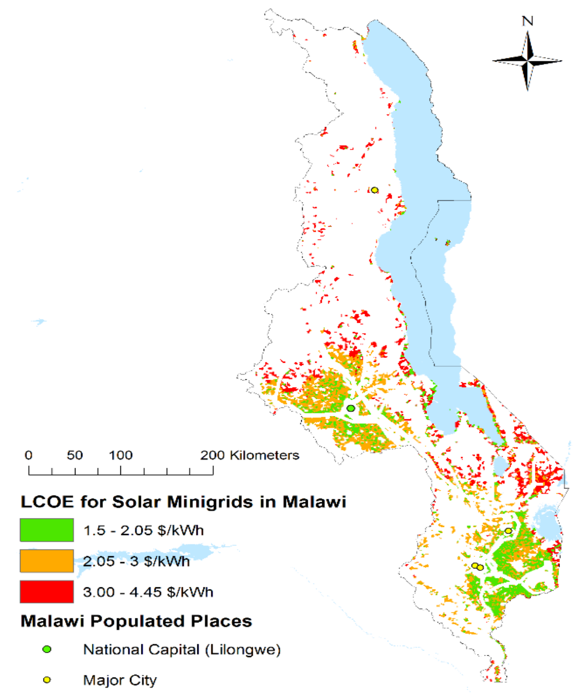

Figure 31 Cost of Energy for Optimally designed Solar Microgrid in Malawi

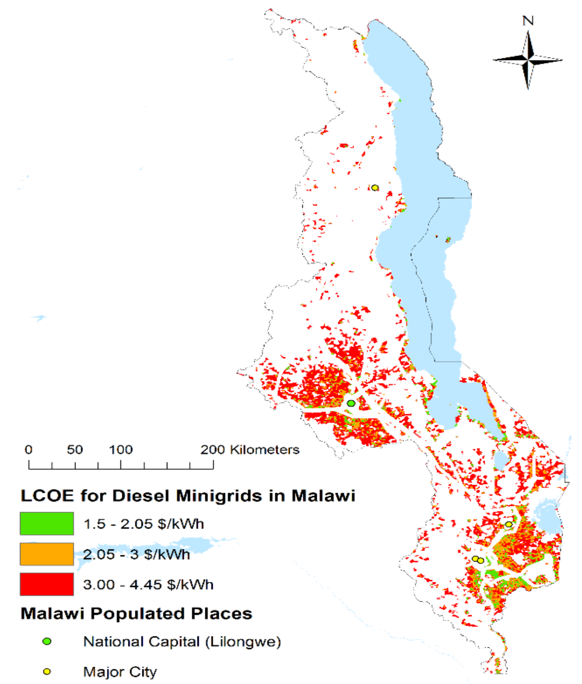

Figure 32 Cost of Energy for Optimally designed Diesel Microgrid in Malawi

Figure 33 shows the split of the population of Malawi by most appropriate technology, based on the population density thresholds used to assign technologies. It is noted that the population density data this figure is based on dates from 2015, and this is a purely static figure based on this data and does not account for population growth/migration or additional transmission lines. That said, the proportion of the population shown here as being most suited to grid connection may be an overestimation, as it considers all individuals within a 2km buffer around existing and planned grids (and areas of bright night-time lights) as being best served by grid connection or expansion of existing infrastructure. It does not consider that that many remain unserved in these regions as an ‘under the grid’ population due to high connection costs, informal settlement status or other political concerns. Whilst the quantification of this population is beyond the scope of this study, those living ‘under the grid’ may provide a potential market for high-capacity micro-grids despite the proximity to existing infrastructure.

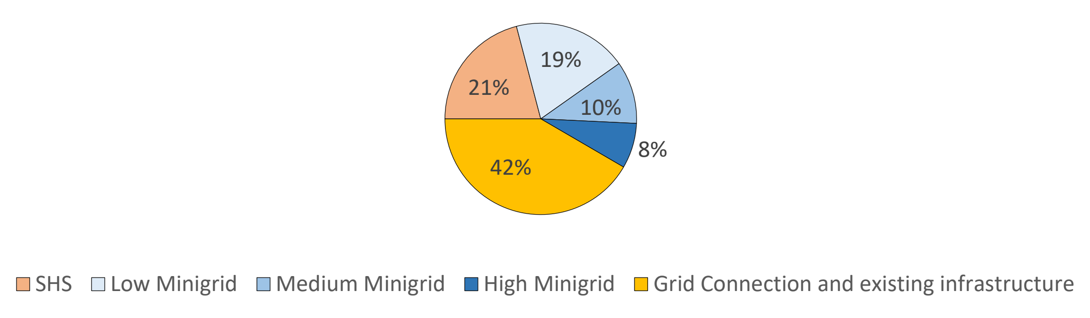

Figure 33 Percentage split of Malawian population based on population distribution and the thresholds shown in Figure 5

Based on these population density thresholds, the market potential for microgrids in Malawi is 37% of the total population, or approximately 6.5 million people. The CAPEX and OPEX cost variations are dominated by the microgrid size, and so in Figure 34 and Figure 35, the highest costs can be seen to be within high population areas suited to high-capacity grids. Conversely, these areas are also the areas exhibiting the lowest LCoE, benefiting from both the lower fuel prices for diesel grids, the diversity of demand from the larger base of customers for an individual grid and lower maintenance costs due to accessibility and proximity to maintenance hubs. The CAPEX and OPEX findings have been compared to the African Minigrids Developers Association Benchmarking Africa Minigrids study[293], showing the results to be comparable to other mini-grids in Africa, shown in Table 33.

Table 33 Comparison of CAPEX and OPEX findings with benchmarks

	Market Assessment findings	**AMDA Benchmarking**
CAPEX per Customer	USD 828 – 1069	USD 733 - 1,555
OPEX per customer per month	USD 4.1 – 4.17	USD 2.50 – 6.00

Weighting the CAPEX and OPEX for the optimal solar microgrids by the number of systems required to provide electricity to everyone within the microgrid threshold regions gives values of $1.2bn and $86.2m per year, respectively. This equates to an average capital investment of approximately $185 per person and an average operational expense of $13 per person per year.

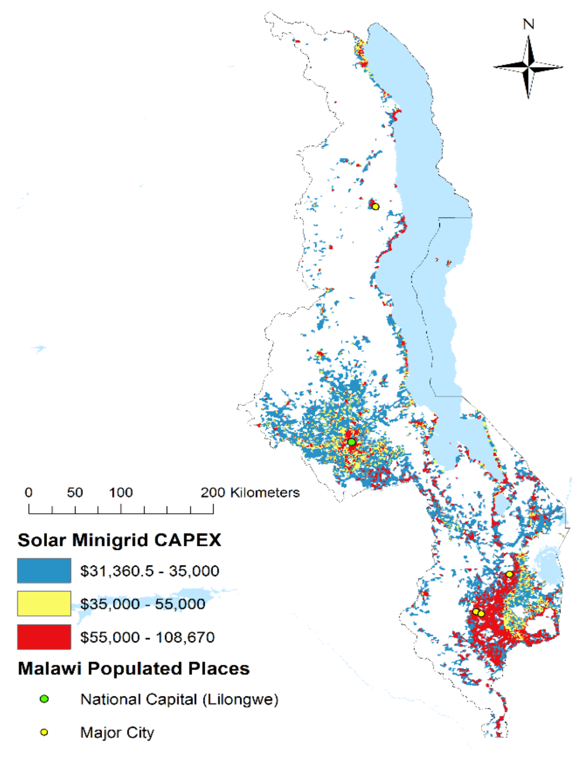

Figure 34 Capital investment required for the optimal micro-grid capacity/design at each location

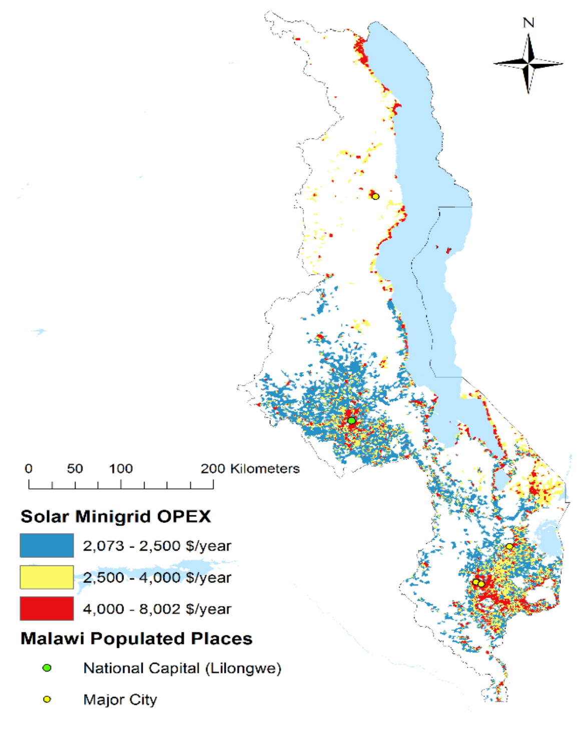

Figure 35 Annual operational costs (including fuel costs) required for the optimal micro-grid capacity/design at each location

4.4.5 Process: Mapping the Malawian solar microgrid ecosystem

Table 34 provides an overview of the solar microgrid ecosystem in Malawi, presented in relevant themes with a summary of the status for each theme and the implication for SMSEs. A more detailed overview of the Malawian microgrid ecosystem is presented in Appendix 7.7. Regulatory guidance refers to mini-grids, of which microgrids are a subset and nomenclature has been changed to microgrid for clarity. The mapping exercise reveals some opportunities promoting and many challenges hindering the feasibility of SMSEs in Malawi. None of the challenges rule out the feasibility of SMSE entirely, and recommendations are given to overcome these barriers in Chapter 5.

Table 34: Mapping the Malawian Solar Microgrid Ecosystem

Theme	Status	Implication
Policy	Several policies exist to promote microgrids including National Energy Policy [276], Malawi Minigrids framework [281] and Malawi Renewable Energy Strategy [278]	Government support provides clarity and confidence in the microgrid market, and frameworks developers can follow.
Regulatory	The Malawi Energy Regulatory Agency offers guidance and support for microgrid development and "is committed to development of microgrids, especially in rural areas in order to complement Government's policy on increasing access to modern and clean energy at national level" [292]	A strong regulatory body avoids poor quality installations negatively affecting the sectors images
Financing and Cost of credit	Access to finance and capital for investment is a challenge as energy business models are not commonly understood by Malawian banks, and financial institutions tend to be risk averse with energy projects [288] with limited access to credit from formal providers, and cost of credit prohibitive factor. Interest rates are extremely high, with banks regularly charging in excess of 40% [289]	Significant barrier to scaling through traditional financing routes. Until more pilots are implemented, providing evidence on financial sustainability and reducing risk for credit providers
Volatile macro-economics	Exchange rate fluctuations have impacted on renewable energy projects finances, especially when components are purchased from abroad	Business planning becomes challenging for microgrid developers, increasing perceived risk for investors
Donor funding	Majority of energy projects in Malawi funded by overseas donor grants [155], receiving criticism for both being insufficient to achieve SE4All targets and distorting markets and hindering private sector initiatives [217].	In the short term, it is likely SMSE will reply on donor funding and should be cognisant of relevant programmes, opportunities, with a view to transition to financial independence
Limited Government Funding	Government financial support for minigrid initiatives is limited, as the majority of funding is dedicated to expanding rural electrification through the Malawi Rural Electrification Programme MAREP which primarily supports national grid extension	Funding through MAREP for microgrid projects would accelerate deployment significantly, and policy advocacy towards this aim needs to be undertaken.
Lack of proven business models	Despite emerging private sector pilot projects there are no proven sustainable business plans showing payback and return on investment for microgrid systems in Malawi.	Early stage microgrid project will focus on pilots, with a strong research aspect to trial, understand and share business model innovation
Low Ability and Willingness to Pay	Customer base comprised largely of low income subsistence farmers with low ability and willingness to pay. Without subsidies, microgrid developers will face challenges to set tariffs that balance customer's low ability to pay with sufficient income for financial sustainability	Microgrid developers will need to provide innovative tariffs, fee for service for lower income customers, while conducting research and advocacy for subsidies to lower tariffs
PUE	There is generally a lack of rural businesses, unlike many areas of East Africa, where solar microgrid power commonly replaces existing diesel generators [294]. Maize Milling is common in rural areas of Malawi, however solar PV powered maize mills are still at pilot stage in Malawi	Microgrids providing domestic services only will have lower revenue, and developers should target agricultural PUE
Capacity	Human resources for microgrid development and implementation are similarly lacking at all levels including	Developers will struggle to find skilled staff. Government and academia can support

	negotiation, finance, contracting, regulations, technology, partnerships, planning, data and IT	training initiatives, and private sector can offer in house training.
Mobile money	In Malawi, mobile money operators including Airtel and Telecom have not yet reached a critical mass to allow cheap enough transaction fees for customers.	Mobile money can increase efficiency and transparency of payments, and microgrid business models will likely be more expensive and less efficient until these barriers are removed.
Supply chain	Accessing components for microgrids (including generation, distribution, batteries, monitoring and control, payment platforms) is a challenge for project developers, and tests sustainability of systems with poor access to replacement parts	Acknowledging this will be a problem in the short term, as more microgrids are implemented supply chains should be strengthened, with government support.
Availability of Appliances	Beyond electricity supply technologies, availability of quality electrical equipment and appliances is limited for consumers in homes, enterprises and public facilities. Access to high efficiency products including light bulbs, TVs, fridges, and other appliances is particularly important for rural consumers relying on systems with limited generating capacity	Linked to supply chain issues, these will present a barrier in the short term but can be overcome as market grows.

4.4.6 Market assessment: Outputs, feasibility check and discussion

4.4.6.1 Outputs

The market potential for microgrids has been estimated to be 37% of the total population, or approximately 6.5 million people, with national maps produced to indicate the most suitable locations for microgrids base on LCoE. In terms of informing the next step of the methodology, the following guidance has been gained:

- CAPEX and OPEX cost variations are dominated by microgrid size, with high population areas suited to high-capacity grids offering the lowest LCoE.
- In every location within the inclusion zone the LCoE for a solar microgrid was less than a diesel microgrid in the same location, this corroborates the impetus for solar microgrids. Although the inclusion of diesel has been found to reduce LCoE, solar only grids have been chosen for business modelling at scale based on low carbon motivations of the implementing partner.
- More accessible locations (closer to cities and towns) exhibit lower LCoE, these site should be prioritised especially for planning of portfolios early on in Malawi’s nascent market

4.4.6.2 Feasibility checks

The high market potential presents as a positive feasibility check, i.e. that there is an adequate market potential for an SMSE operating at scale. Eco-system mapping has highlighted both enabling and stymying characteristics in the microgrid and energy access sector in Malawi. Key barriers that need to be addressed include access to finance and capital for investment, volatile macro-economics, lack of proven business models, local capacity and supply chain constraints. None of the barriers identified completely prevent microgrid implementation, and are addressed with recommendations for barrier removal presented in Section 5.2.

4.4.6.3 Discussion

The analysis indicates that potential exists for microgrids in Malawi to achieve the policy goals of increased rural electrification, however the LCoE is high and barriers exist in the ecosystem for widespread deployment.

In the most remote regions of Malawi the cost of energy is anticipated to be highest, due to lower population densities (and thus smaller system sizes), and higher maintenance costs. Coupled with the higher cost of energy, these populations are also likely to have a lower ability to pay given the rural-urban disparity of wealth in Malawi [267], further compounding the problem. In general, microgrid systems are most cost effective where the connected households are relatively close together (that is, where population density is higher), limiting the extent and costs of the local distribution network. Microgrids are assumed to generally be a preferable technology over SHS, where viable, given the potential for microgrids to cater for higher loads and benefit from diversity of demand (and diversity of generation in the case of hybrid systems). For these, it is assumed that where solar microgrids are viable, they are the preferred option of electrification, although in some situations this may not be the case.

Conversely, no consideration has been made here with regards to the cost of the required generation capacity to increase the grid connection rate of Malawi from 12.7% [84] to the 42% identified here. Detailed grid studies are required to understand the capacity of current generation, transmission and distribution assets to meet this predicted demand, comparisons should be made between the per capita costs associated with grid reinforcement and additional generation capacity and the costs for microgrid development identified here.

4.5 Business modelling for scale up in Malawi

The final stage of the methodology investigates the financial sustainability of a SMSE operating at scale in Malawi, utilising primary case study data provided by two pilot microgrids installed in the Dedza district of Malawi as described in Section 4.6. The business modelling at scale has been conducted for the first step of expansion for a SMSE in Malawi, looking at the feasibility of a portfolio of 10 microgrids. Data is provided through a site prospecting exercise, CAPEX costs from two pilot microgrids, and demand and operational costs from 12 months operational data from one microgrid. The scope of methodology application reflects resources and primary data available, and although is only a first step towards an assessment of a nationally operating SMSE, provides value in informing the feasibility of a SMSE in Malawi as well as testing the validity of the methodology.

4.5.1 Inputs: CAPEX and OPEX at scale

CAPEX cost inputs taken from analysis of two EASE microgrid installations are summarised as per kW, per customer or per microgrid, scaled as appropriate for design assumptions on sites included in the portfolio modelling, summarised in Table 35 with a full breakdown of CAPEX costs for both microgrids outlined in Appendix7.8. As the first microgrids of their scale installed in Malawi, these CAPEX costs are higher than benchmarks and reductions through economies of scale are explored through sensitivity analysis in Section 4.5.6. Development costs for inception activities, environmental and social impact assessment, feasibility studies are covered by central business overheads outlined in Table 37.

Table 35 CAPEX costs used for Business scale up modelling

CAPEX Component	Cost
PV Modules (USD/kW)	$ 322.33
Racking (USD/kW)	$ 398.64
Generation installation (USD/kW)	$ 107.87
Solar PV Inverter (USD/kVA)	$ 221.75
Battery Inverter (USD/kW)	$ 393.47
Storage (USD/kWh)	$ 583.79
Distribution (USD/per customer)	$ 551.55
Customer Connections (USD/per customer)	$ 104.05
Fixed Generation costs - Shipping container (USD)	$ 15,498
Smart metering inc shipping (USD/per customer)	$ 66.77
Distribution Installation (USD/per customer)	$ 323.85
Fees (USD)	$ 3,955

The pilot microgrid described in Section 4.6 offers 12 months of OPEX cost data, adapted for analysis[1] and summarised in Table 36. Costs are segregated into fixed and per customer and scaled appropriately for sites modelled within the portfolio. Operating a fleet of microgrids can offer cost savings through efficiency measures, and sensitivity of cost reduction is explored in section 4.5.6.

Table 36 OPEX assumptions for business modelling at scale

OPEX component	Month cost (USD)	Annual cost (USD)	Fixed/per customer
Data for 3G router (16,800 MWK per month)	$ 20.16	$ 242	per customer
Steamaco SaaS Fee 0.54 USD per meter	$ 32.40	$ 389	per customer
Steamaco SMS fees (average)	$ 23.84	$ 286	per customer
Site agents (1 x 50,000 MWK per month)	$ 60	$ 720	Fixed
Security Guard (50,000/m)	$ 60	$ 720	Fixed
Generation and Distribution Maintenance (600,000 MWK/yr)	$ 60	$ 720	Fixed
TOTAL SITE BASED OPEX COSTS	*$ 256*	*$ 3,077*	

A summary of operating overheads for the SMSE comprising staff and wider business costs have been provided from pilot project partners United Purpose as realistic in-country costs and are outlined in Table 37, with a more detail description provided in Appendix 7.9.

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[1] The number of site agents has been reduced from two to one

Table 37 Central Business Overheads

Item	Cost
Staff	$ 64,840.11
Admin Overheads	$ 4,400.00
Travel	$ 14,412.43
Community engagement	$ 5,282.49
Total	*$ 88,935.02*

4.5.2 Input: Market potential and location of portfolio sites

Dedza district has been chosen by implementation partner United Purpose (UP) as an area to conduct the next step of microgrid operations in Malawi, and the area of focus for the business scale up modelling. The district was selected by UP as one they are active in and logistically sensible to expand operations in, while the district shows potential for solar microgrid deployment in the market assessment geographical assessment. Further modelling on a district scale would reveal the explicit district wide market potential but is out of scope of this research and unnecessary for the use of the methodology for the 10 chosen sites.

In addition, the guiding outputs of the market assessment (Section 4.4.4) are summarised below:

- Choose higher capacity microgrids: the larger microgrid sites have been selected, assuming all customers at the site will want a connection
- In every location within the inclusion zone, the COE for a solar microgrid was less than a diesel mini-grid in the same location. Solar only grids have been chosen for business modelling
- More accessible locations (closer to cities and towns) exhibit lower LCoE. These site have been prioritised.

4.5.3 Input: Demand and ability to pay

The site selection exercise described in Section 4.5.4 identified indicators of economic activities at the portfolio sites (e.g. presence of a market) as well as number of potential customer segments (residential, commercial and institutional). Hourly load profiles for 1 year (8760 data points) from pilot site Mthembanji are used as load inputs for Odyssey. Customers are segregated into residential, commercial and institutional, with the number of each customer segment in the portfolio site multiplied by the appropriate 8760 customer segment data set from Mthembanji to obtain the final demand.

AWTP estimates for the sites are also taken from Mthembanji. As described in more detail in 4.6.3.6, tariff setting has been conducted over time as a negotiation with the community, and the tariffs used for modelling are taken as affordable for the community. The assumption of AWTP applicability from one site to another in the same district can be tested through further pilot data, explored more in the discussion section.

4.5.4 Process: Site selection for fleet of microgrids over chosen region

A site prospecting exercise carried out by United Purpose identified a long list of 20 sites in Dedza, from which the most viable 10 have been selected based on indicators outlined in Section 3.5.1. Figure 36 shows the location of the chosen sites, and a full list of the information captured in the site selection prospecting exercise is listed in Appendix 7.9.

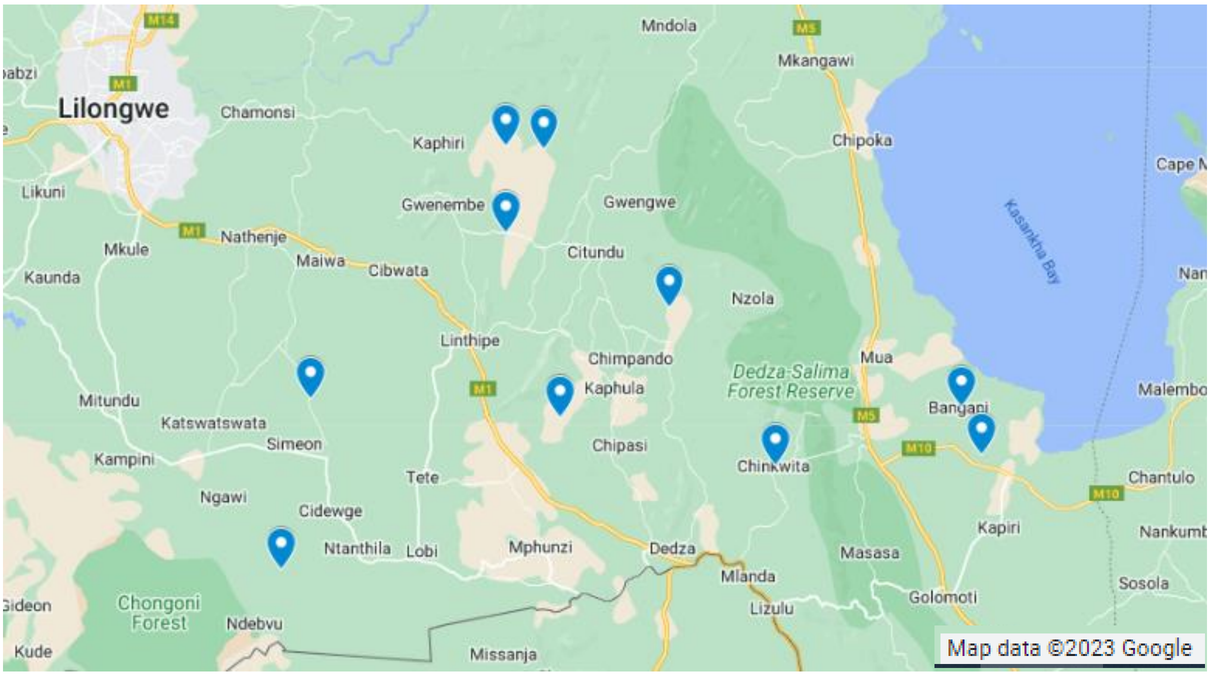

Figure 36: Location of portfolio sites (Map source Google Maps)

4.5.5 Process: System design of multiple sites and tariff setting

HOMERPro optimiser designs systems for the number of customers at each site in the portfolio. Assumptions and inputs for the system designs are outlined below, while a summary of the system sizes for each microgrid in the portfolio is shown in Table 38.

- Solar resource calculated through HOMERPro using the GPS coordinates provided by the site prospecting exercise, see Appendix 7.10.
- Demand assumptions utilise measured load profiles from pilot data (see section 4.6.3.4) as 8760 datasets compiled for each customer segment (residential, commercial and institutional), described above.
- Demand growth set as 2% per year up to year 10, with an 18% generation system oversizing included in HOMERPro to cater for this. Replacement costs are required at year 10 for inverters and batteries.

- Tariffs are assumed to be the same as Mthembanji at all microgrids sites. See Section 4.6.2.1 for more details
- Additional assumptions for HOMER and financial modelling are presented in Appendix 7.11.

Table 38 Portfolio system sizing

Project Name	Total Customers	Solar PV Capacity (kW)	Storage Capacity (kWh)	Total CAPEX (USD)	Operating Expenditures (USD/yr)
Hinda	411	51	97	542,803	8,440
Kaname	373	38	95	487,953	7,859
Chinkombero	370	51	89	494,166	7,814
Tsoyo	327	43	80	437,839	7,157
Chikuse	323	48	79	440,559	7,095
Kalulu	292	35	76	392,792	6,622
Ndindi	224	24	55	299,534	5,583
Mwambula	158	16	42	217,829	4,574
Mthembanji	60	12	19	101,995	3,077
Kudembe	50	11	20	108,373	2,924

4.5.6 Process: Financial modelling

Two key scenarios are modelled. Firstly, a worst-case scenario where all assumptions are taken directly as above to determine project IRR for each site of the portfolio. Realistic interventions are then introduced through sensitivity analysis to improve economic viability of the portfolio sites, with further financial analysis conducted to understand the performance of the portfolio as a whole.

4.5.6.1 Baseline: Financial results without interventions

The above inputs were inserted into Odyssey, with model outputs for each site including IRR, total revenue, total expenses and average yearly operating margin are outlined in Table 39.

Table 39 portfolio site level economic performance

Project Name	IRR (%)	Total Revenue (USD)	Total Expenses (USD)	Average Yearly Operating Margin (USD)
Chikuse	-2.75	598,078	284,386	15,685
Chinkombero	-4.56	590,353	311,874	13,924
Hinda	-4.28	554,218	241,611	15,630
Kalulu	-4.12	496,742	263,727	11,651
Kaname	-4.37	499,647	223,808	13,792
Kudembe	-9.40	94,294	75,234	953
Mthembanji	-14.64	78,144	77,228	46
Mwambula	-7.57	253,559	173,394	4,008
Ndindi	-6.75	271,665	150,921	6,037
Tsoyo	-5.00	516,796	283,872	11,646

All sites modelled result in a negative IRR, ranging between -2.75% and -14%. Generally, as the size of the site increases (i.e. higher number of customers and larger generation sizes) the IRR is closer to 0, suggesting that larger sites will generate more income from higher numbers of customers. The very low IRR result for Mthembanji shows that the system was oversized, and the number of customers is low for the generation installed and associated costs. The lifetime revenues are higher than lifetime expenses, suggesting that if CAPEX was donor funded the microgrids would be able to cover site based operation costs, with some contributions over the 10 site portfolio to wider business costs. However, the main findings demonstrate that with existing assumptions there is not a financial investment case for the portfolio and the case is unfeasible.

Analysis of results reveals the following reasons for negative IRR, which are used to inform intervention to increase investment case in the next section.

- **High residential load:** The sites all incorporate high numbers of residential domestic customers, resulting in high excess daytime generation. This reduces microgrid utilisation and revenues, lowering IRR.
- **High CAPEX and OPEX**: costs taken from two microgrid sites are deemed to be high due to the nature of being the first microgrids of their size to be installed in Malawi. Economies of scale will reduce these costs.
- **Tariff bundles:** Tariff structures are currently set as a monthly fee for residential customers, not increasing with growth over time. Although this helps ultra-poor customers, it doesn’t allow for load growth over time, limiting the demand and associated revenue, reducing IRR further.

4.5.6.2 Results: Interventions

Sensitivity analysis on the input assumptions conducted introduces realistic interventions to improve site based the IRR. The interventions are based on cost reductions through operating at scale and are outlined with justifications in Table 40.

Table 40 Intervention to improve IRR of project sites

Intervention	Justification
Reduction in OPEX (20%)	Operating multiple microgrid sites offers efficiency savings
Reduction in CAPEX (20%)	Bulk purchasing offers economies of scale
Introduction of Anchor load	Excess daytime electricity is observed due to high residential load. An anchor load utilising 50% of excess electricity is introduced. Anchor tariffs are set as 0.5 USD/kWh, based on existing pilots[2]
Grant contribution to portfolio CAPEX (50%)	As a nascent market, grant contributions to project costs are expected, 50% deemed reasonable based on similar nascent microgrid programmes .[295]
Changing residential tariffs to set per kWh	Monthly tariff costs (see section 4.6.2) help newly connected customers budget their energy use, but limits demand growth which has a big impact on financials, changing tariffs to per kWh allows for customers to utilise more energy and improves financials

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[2] Email correspondence with Odyssey technical support on typical anchor loads of SSA minigrid projects.

The results from repeating the Odyssey model with the interventions above are shown in Table 41. All sites now have positive IRRs between 9.1% and 15%, with payback periods ranging from 14 to 17 years. These results indicate a positive investment case for the microgrids at individual sites and allowing justification to run the portfolio model in Odyssey.

Table 41 Portfolio financial results with sensitivity interventions to improve IRR

Project Name	IRR (%)	Simple Payback (yr)	Total Revenue ($)	Total Expenses ($)	Average Yearly Operating Margin ($)
Chikuse - Anchor	15.0	14	931,071	194,614	36,823
Chinkombero - anchor	13.0	15	924,546	212,089	35,623
Hinda - Anchor	11.9	16	932,942	220,326	35,631
Kalulu - Anchor	12.0	15	693,389	172,766	26,031
Kaname - Anchor	14.5	14	1,011,337	209,173	40,108
Kudembe - Anchor	9.1	17	169,938	60,956	5,449
Mthembanji - Anchor	9.2	17	168,119	64,891	5,161
Mwambula -- Anchor	9.5	17	339,571	107,389	11,609
Ndindi - Anchor	10.8	16	506,143	137,694	18,422
Tsoyo - Anchor	14.2	14	914,436	192,802	36,082

A portfolio model was then run with the microgrids sites listed above, and wider business costs included (Table 37). Results for the portfolio of microgrids deployed by an SMSE at scale indicate an unlevered IRR of 5.23%, and equity IRR of 4.43%, and an equity payback period of 17 years. The income statement for the portfolio showing Annual Net Income, Earnings Before Taxes (EBT), Earnings before Interest and Taxes (EBIT), and Earnings before Interest, Taxes, Depreciation and Amortization (EBITDA) is shown in Figure 37, and the cumulative free cash flow to equity in Figure 38.

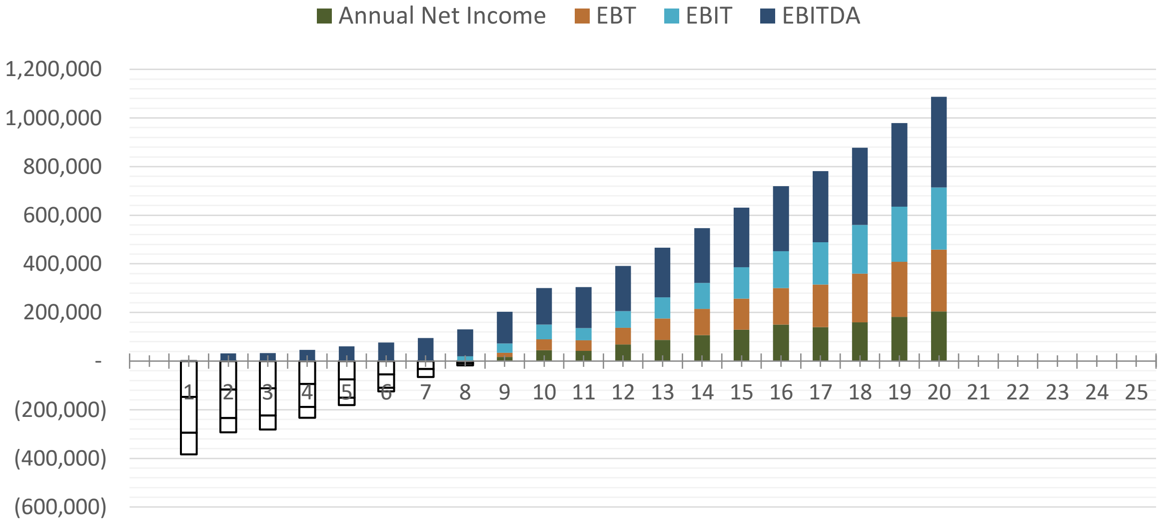

Figure 37 Income Statement for modelled portfolio

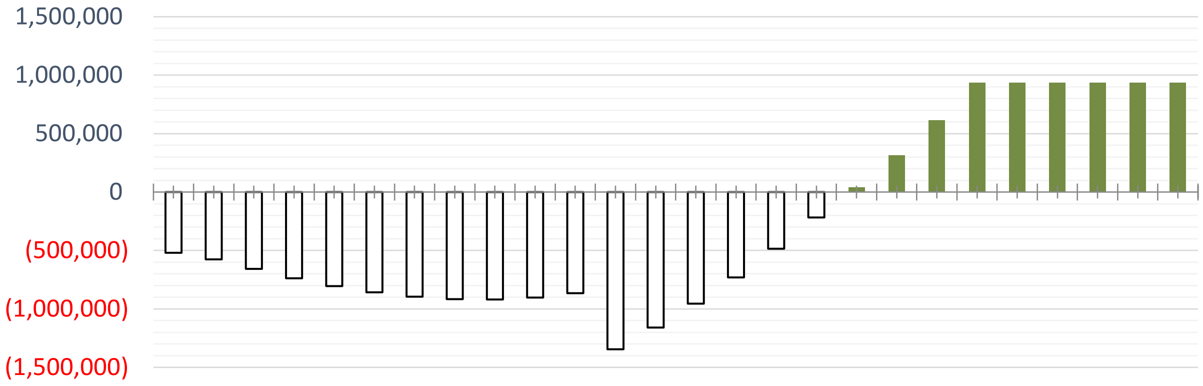

Figure 38 Cumulative Free Cash Flow to Equity

4.5.6.3 Sensitivity analysis

Odyssey allows for sensitivity analysis to explore impact of multiple parameter on the portfolio IRR. Figure 39 shows how tariff changes can have a significant impact on portfolio IRR, with a 40% increase in tariffs resulting in an 8.1% increase in IRR. Figure 40 shows the impact of change in consumption, indicating that a 20% under expected demand would reduce the portfolio IRR to below 0% making the investment unsustainable, while a 20% increase in demand would provide an IRR of 4.2% higher.

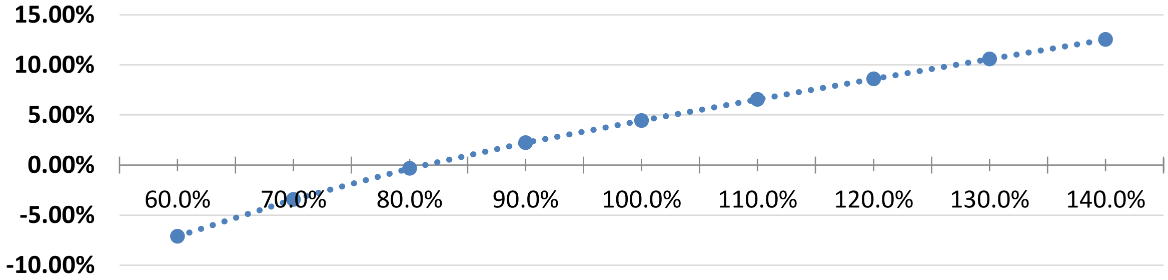

Figure 39 Sensitivity analysis on all tariffs

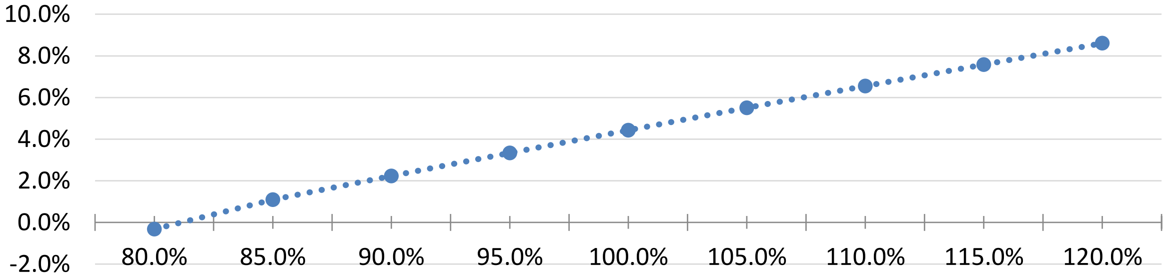

Figure 40 Sensitivity analysis on all consumption

4.5.7 Business modelling for scale: outputs, feasibility check and discussion

4.5.7.1 Outputs

For this application of the methodology, the scale up scenario focussed on the Dedza district, with sites identified through primary data collected from a site prospecting exercise. The 10 sites presented offer a realistic next step on the path to a national SMSE. Reiterations of this step of the methodology allow for detailed analysis on different scale up scenarios, investigating the financial sustainability of expanding further in Dedza, or entering new or multiple districts across Malawi.

4.5.7.2 Feasibility Check

For a worst-case scenario, with CAPEX and OPEX costs modelled exactly as current pilots, all site IRRs are negative and an SMSE is unlikely to be financed and therefore financially unfeasible. However, with interventions to reduce CAPEX and OPEX, changing residential tariffs to per kWh, and including a 50% CAPEX grant, all sites have a positive IRR and the portfolio offers an investible return on investment, with significant contributions to wider SMSE costs. With the intervention assumptions applied, a SMSE is feasible in Malawi. Further discussion on the feasibility of SMSEs in Malawi combining the financial modelling with further primary data gathered from pilot in section 4.6 is offered in the discussion in section Chapter 5.

4.5.7.3 Discussion

The use of Odyssey presented here offers a tangible step to SMSEs reaching scale in Malawi, as the industry standard tool links microgrid developers to investors using standardised data inputs. The use of data from pilot microgrids analysed and presented is a first for Malawi and offers significant progress in providing transparency in a grey market. As no previous published literature could be found on financial sustainability of a portfolio of microgrids in Malawi, the outputs are a first step in filling a wide gap in literature. However, the sample size is still low, with measured data only from one microgrid. As the methodology is repeated with further microgrids the uncertainty is reduced, and the investment case improves.

The results indicate that SMSE hold potential to be feasible, if interventions can be made including reduction in CAPEX, OPEX and the introduction of grant funding for CAPEX. As Malawi is still a predominantly donor funded initiatives, it is reasonable to expect donor CAPEX as part of an investment portfolio, and for investors to expect patient returns, i.e. long paybacks. The sensitivity analysis shows the significant impact increasing or reducing tariffs has on the portfolio IRR. Obviously the maximum tariff increase of 40% would be unfeasible with current customer ability to pay, but as the microgrid promotes economic activity, customer affordability and demand for electricity increases, improving portfolio financial performance. The sensitivity of demand shows how important understanding customer consumption is and confirms the need for accurate load predictions though measured load profiles.

The main reasons for a low/negative IRR using the initial parameters are due to a load profile that caters more to residential users rather than commercial, productive, or anchor loads; anchor loads and high CAPEX and OPEX costs without revenue (tariff rates) meeting these costs. The high residential use offers a challenge and potential conflict for social enterprises: connecting all customers that want or need electricity, or returning a decent profit. These challenges are dissected with recommendations proposed to overcome them in Chapter 5.

4.6 Piloting, monitoring and evaluation using a social impact focussed Key Performance Indicator framework in Malawi

Since commissioning of the microgrid installed under the EASE project in July 2020, data collection has been ongoing for technical, economic and social impact performance parameters. This section follows the methodology recommendations made in Chapter 3 by presenting primary data gained through microgrid implementation in order to test the validity of the methodology as well as provide valuable insight for informing the microgrid business model and the wider Malawian microgrid ecosystem. The data collection frameworks used at Mthembanji are presented, which include smart meters, remote monitoring and customer journey survey conducted through field enumerators. Under themes of technical, economic and social impact, selected KPIs are outlined, before presenting microgrid performance data on those KPIs, highlighting specific implications for microgrid technical and business design and relevance to policy and the wider microgrid ecosystem. Some KPIs from the full list presented in Chapter 3 have been omitted due to lack of relevance or applicability Mthembanji, while others have been discounted to keep the research scope within human and data collection capacity of the EASE programme that has enabled data harvesting.

4.6.1 Case study KPIs and data collection frameworks

Mthembanji microgrid was installed in July 2020, allowing 2 years of available data at time of writing. The period of data collection and analysis presented runs from January 2021 to December 2022, representing a full year to allow for seasonal trends to be observed. Technical, economic and social impact KPIs monitored for the Mthembanji microgrid are indicated in Appendix 7.3, while data collection methods are outlined below.

4.6.1.1 Smart metering

The microgrid utilises SteamaCo [16] smart meters, offering an innovative solution to monitor energy use, lets people pay for power using their mobile phones, and quickly troubleshoots any problems. SteamaCo’s mobile-enabled smart meter, bitHarvester, allows for both remote switching and remote data logging, keeping assets in constant contact with a cloud platform and allowing users to manage connected assets in real time through a unified online interface. For Mthembanji, real time data on revenue, demand and smart meter uptime has been accessed through the cloud platform for detailed analysis.

4.6.1.2 Remote monitoring

Generation and storage remote monitoring data has been accessed through Sunnyportal [296], an Internet portal offered through SMA which enables mini-grid system operators and researchers to monitor and configure systems and to visualize system data. Data is logged at 5-minute intervals and available for weekly or daily download.

Battery temperature is tracked through a custom built temperature logger[3] installed in March 2022 to measure internal, external and battery temperature, logged at 10 minute intervals and exported to a cloud platform via the site's 3G Wi-Fi network.

4.6.1.3 Surveys

'Customer journey' surveys were conducted through United Purpose (UP) enumerators with all microgrid customers through smart phones using the Kobocollect app. Surveys uploaded to Kobocollect's online platform were downloaded for analysis as .csv files. Ethical approval was applied for and granted through the University of Strathclyde's Ethics Committee. Following a baseline survey prior to microgrid installation, two follow up surveys have been conducted, with a description and dates outlined in Table 42.

Table 42: Date of surveys

Date	Type of survey	Months since installation
August 2019	Customer journey baseline	
July 2020	Microgrid installed	
May 2021	Customer Journey follow up 1	10
January 2022	Customer journey survey follow up 2	18

4.6.1.4 Project management documentation

EASE project partners University of Strathclyde and UP utilised a shared file system for storing relevant project documents including invoices, technical designs, project Gantt charts, photos and budget spreadsheets used to inform the proceeding analysis.

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[3] Developed under work funded through Innovate UK Energy Catalyst Round 6: Project Number 10528, Productive Use of DC Solar Power in Africa to Improve Quality of Rural Life. Project team Dr Matt Little and Dr Richard Blanchard Further details can be found at https://www.lboro.ac.uk/research/crest/research/groups/re-for-development/facilities/

4.6.2 Field Experiences

The data for this sections comes from the Authors experience in being the lead project developer, along with informal interviews with field staff engaged with the microgrid deployment. It provides a technical and operational summary of the installed system microgrid along with key lessons learned through implementation.

4.6.2.1 System overview

The 11.5kW microgrid installed in Mthembanji provides wired connections to 60 customers for domestic and commercial use including lights, phone charging, TVs, fridges and other productive uses. The microgrid is intended to offer a new method of rural electrification that allows for more electricity and higher impact than solar home systems currently offered, but cheaper and quicker to implement than larger capacity minigrids currently deployed in Malawi. Figure 41 shows the generation hub of the microgrid including PV array and mounting with shipping container housing the storage and power electronics.

Figure 41 Installed microgrid at Mthembanji

The system has a central generation system with solar PV panels, lithium ion storage and electronics supplied by Sustain Power in South Africa: their shipping container houses inverters and Lithium-ion batteries from German manufacturers SMA and Tesvolt. The component sizing of the generation system followed cost negotiations with the supplier and takes account of future growth, outlined in Table 43.

Table 43 Component Specifications

Battery specifications	48V, Lithium Ion Batteries
Battery Capacity (kWh)	19.2 kWh
PV specifications	Monocrystalline, 320W
PV Array Size (kW)	11.52kW peak
Battery Inverter Size (kVA)	8 kW
PV Inverter	10 kW

Electricity from the generation hub is distributed through overhead wires on 9m poles to customer premises. The distribution grid is analogous to that of a 240V single phase Low Voltage feeder from a secondary substation on the Malawi ESCOM grid. Smart meters mounted on the distribution poles automatically disconnect customers when their balance runs low, as well as setting power limits to protect the system from misuse. The generation hub was commissioned and distribution grid installed by Malawian electrical contractor BNG Electrical, based in Lilongwe.

Through smart meters, innovative and dynamic tariffs have been tested and adjusted, following extensive community engagement and feedback, summarised in Table 44. Tariffs are paid through site agents in a PAYGO format, where customer balances are topped up through the SteamaCo platform.

Table 44 Tariffs at Mthembanji

Bundle	Services	Payment type	Cost	USD/kWh
Banja Monthly ***(Household)***	A set allocation of energy (260 Wh per day) which approximately equates to a daily service of: 3 lights for 3 hours 1 light for 8 hours 1 hour of TV 2 hours of phone charging	Monthly service fee	MWK 3,500 per month (MWK 116 per day)	$0.54
Ufulu (Freedom)	Unlimited electricity paid for per unit. A cheaper rate applies for higher use.	Pay as you Go	0-2 units: MWK 1,200/kWh 2-8 units: MWK 960/kWh Over 8 units: MWK 780/kWh	$1.44 $1.15 $0.94
Ufulu Daytime	Daytime discount 75% reduction in standard Ufulu costs	Pay as you Go	0-2 units: MWK 300/kWh 2-8 units: MWK 240/kWh Over 8 units: MWK 195/kWh	$0.36 $0.29 $0.23
Midzi (Community)	Electricity for Schools, Churches or other community groups based on your needs	Pay as you Go	3 units for free, then MWK 1,200/ unit	$1.44

4.6.2.2 Installation experiences

Following significant delays due to Covid-19 restrictions, regulatory hurdles and programme related administrative challenges, the installation team finally completed the distribution grid and customer premises wiring in June 2020. PV modules were installed and wiring checks completed before the system went live in July 2020, with customers switching on lights for the first time. A week of testing involved monitoring battery state of charge to assess whether the design assumption of load and system sizing were correct, and dealing with technical issues getting the smart meters online, as well as calibrating mobile networks between the UK and Malawi. The site was visited by representatives from the Malawi Energy Regulatory Authority (MERA), who assessed the quality of the installation, granting approval for the sales of electricity.

The development, installation and commissioning of the microgrid faced serval challenges resulting in significant delays to planned schedules. Table 45 highlights key challenges and lessons learned from field experiences, along with the implications for refining the methodology and microgrid scale up. Evidence has been gained through the Authors experiences and also through interviews with UP staff.

Table 45: Experiences gained through development and installation

Theme	**Experiences**	**Lessons Learnt to inform future installations**
Local Stakeholders	Time taken to gain local permissions, including engagement with District Council, Traditional Authority Leaders and community was lengthy. Challenges setting up an energy committee, local politics	Standardising approaches to local stakeholders and community sensitisation can save time on developments.
Engaging with local and International organisations	Using Sustain Solar, an experienced international supplier provided valuable in technical support specifically with the generation design. Similarly using qualified and experienced local contractor was essential for installation and maintenance arrangements.	Paying for highly qualified local and international contractors is worthwhile in the early stages, eventually the high costs can be mitigated through training in-house staff.
Regulatory/ Policy	Initial uncertainty on regulatory requirements and licensing, clarity gained once minigrids framework came out. Producing an Environmental and Social Management Plans caused lengthy delays and utilised high amounts of resources.	Lobbying for reduced regulatory requirements, especially for smaller microgrids. Set up an Environmental and Social Management Framework for all mini-grids to reduce having to do an ESMP for each new project.
Financial	Currency exchanges caused budgetary issues. Similarly lack of available foreign capital. Inflation causes prices to fluctuate, sometimes daily making budgeting challenging.	Project managers need to track exchange rates and quantify how changes will affect projects, allowing back-up plans for currency changes.
Supply chain	Procurement challenges with companies that haven't installed microgrids before leading to high prices. Lack of components available locally, necessitating purchasing from South Africa, causing further delays.	Strengthening supply chains, ensuring locally available microgrid components will reduce delays and keep foreign capital inside the country.
Administrative hurdles	Working through bureaucratic processes with large organisations such as NGOs and University caused delays in making payments and auctioning purchase orders	Justification for social enterprise frameworks – more nimble, flexible and efficient

4.6.2.3 Operational experiences

The microgrid has been operated and managed through field staff employed by UP, with technical support from University of Strathclyde. UP have engaged two local site agents through an employment contract to act as vendors for electricity sales, site technicians and customer service officers ensuring adequate communication channels between the community and UP. Local site agents also conduct preventative maintenance including PV module cleaning and battery care, as well as reporting any technical problems arising. UP employ MERA accredited BNG Electrical as maintenance contractors to conduct quarterly maintenance visits, troubleshoot any problems raised by the local site vendor, replace failed components and wire up new business and domestic connections. Specific experiences gained through the microgrid operation noted by field staff are outlined in Table 46, discussed more in Chapter 5.

Table 46: Experiences gained through operation of the microgrid

Theme	Experience	Lessons for future microgrids
Community Engagement	Significant training required on electricity use, with ongoing refresher training to avoid accidents. Vandalism occurred, requiring further sensitisation Tried setting up a Village Energy Committee – didn't work due to local politics, strong Group Village Head needed to mitigate these issues.	Community engagement should be a key focus embedded in the service offering of a SMSE, with financial and human resources set aside in the business plan to cater for these social requirements, enabling better service, and happier customers.
Technical Issues – Smart Meters	Challenges were experienced with the Steamaco meters, losing network connection and causing blackouts and increasing customer dissatisfaction. Cost of calling contractors out to site were prohibitive.	Challenges with new technology are to be expected, but ongoing reporting of faults to smart meter providers and requesting upgrades to hardware and software will reduce future issues
Ability and Willingness to Pay	Tariff was found to be too high by the community, resulting in complaints and tariff reductions to find an acceptable tariff. Community negotiations are ongoing in this regard.	Ongoing assessment of AWTP is essential for finding tariff sweet spots and ensuring customer satisfaction and sustainable levels of electricity consumption that doesn't further impoverish communities.
High temperatures	During dry seasons the system shut down due to high temperatures. Logging the temperatures has helps to detect high temperatures and adjust the air conditioning accordingly.	Investing in battery temperature logging equipment can prolong battery lifetimes, designing cooling systems adequate for current and future temperatures (expected to rise due to climate change) essential for technical design.

Some of the field experiences, both installation and operation, correspond to findings of the African Minigrid Developers benchmarking report of minigrids in Africa, specifically: coordination and collaboration among all stakeholders is required; regulatory timelines lead to delays in minigrid deployment; and operational expenses can be reduced through remote and automated processes, but require maintenance and repair which incurs takes time and cost [293].

KPIs monitored at the Mthembanji microgrid are described below in technical, economic, and social impact themes, with performance data presented and specific implications for technical and business design of microgrids highlighted, while relevance to policy and the wider microgrid ecosystem are discussed in Section 4.

4.6.3 Technical Indicators

4.6.3.1 System outages

SteamaCo data in Figure 42 tracks both scheduled and unforeseen outages and shows daily communications uptime over the course of a year. The highlighted 50% area denotes when an outage occurred for the majority of a day, either due to smart meter downtime (communications failure) or generation system outages (inverter, PV or battery issue). Disaggregation between smart meter and generation downtime is not feasible under the current system of data collection. Figure 43 shows start date and length of outages for 1 year, revealing 12 outages in 2021, lasting an average of 2.8 days per outage. The number of days in each month where an outage was discovered is shown in Figure 44. With only four months having no interruptions, August and September had the most outages (8 and

7 days, respectively). The data in the figures indicate excessive technical problems leading the microgrid to experience significant downtime, suggesting a crucial area for improvement.

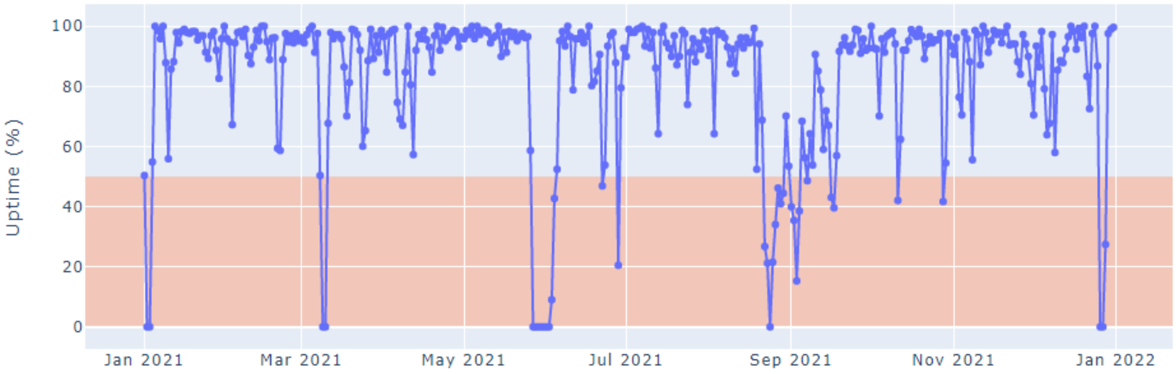


Figure 42: Daily communication uptime 2021

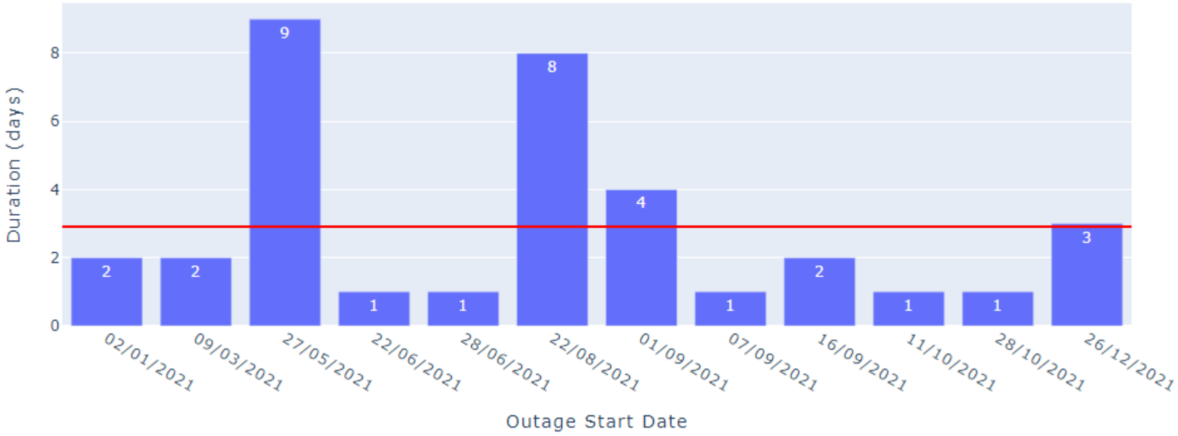


Figure 43 Start date and length of outage for 2021

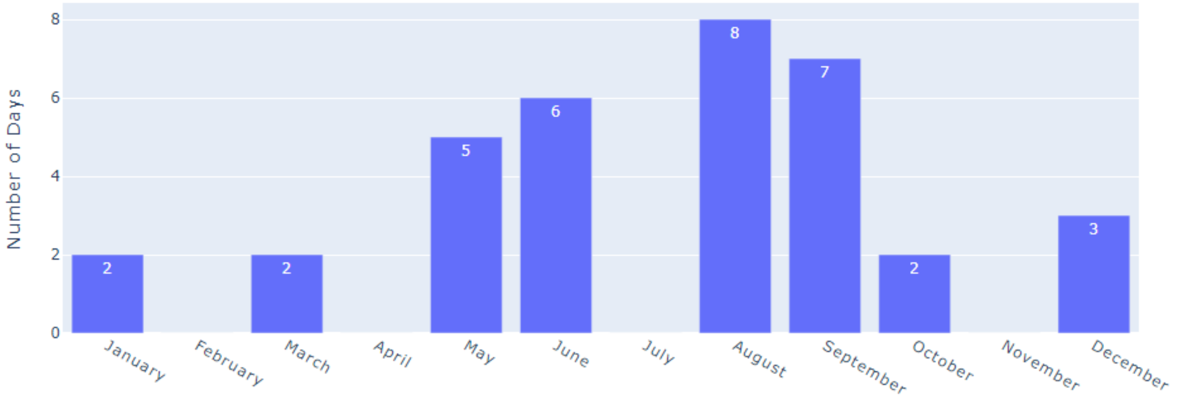


Figure 44 Number of days of outages 2021

4.6.3.2 Generation

Figure 45 shows the variation in monthly power generation over the year, describing seasonal trends following the rainy season in Malawi, with heaviest rains (and associated lower irradiance levels) experienced in February [297]. Generation systems need to be designed to provide required load in worst case scenarios, and monthly outputs should be compared with load demand to match seasonal generation with demand to ensure continuous supply. The annual generation for 2021 of 7,293.9 kWh can be compared to subsequent years when data becomes available to track trends in annual PV generation output, track panel degradation, and predict future microgrid performance, allowing greater insight for futureproofing systems. Figure 46 shows the variation in the daily generation for August 2021, showing a variation between 15.85 kWh and 24.35 kWh, with peaks generally falling on a Friday. Investigating peak days in a week informs tariffs and demand side management strategies, as well as helping to plan business income.

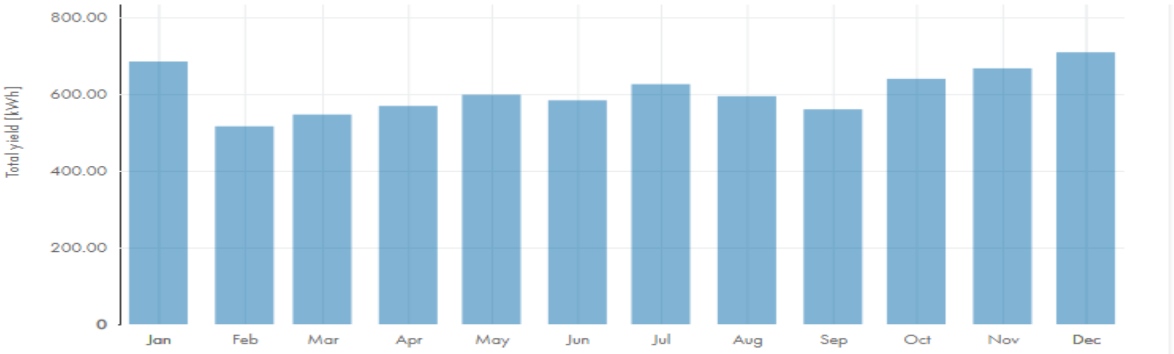


Figure 45: Mthembanji Monthly Generation 2021

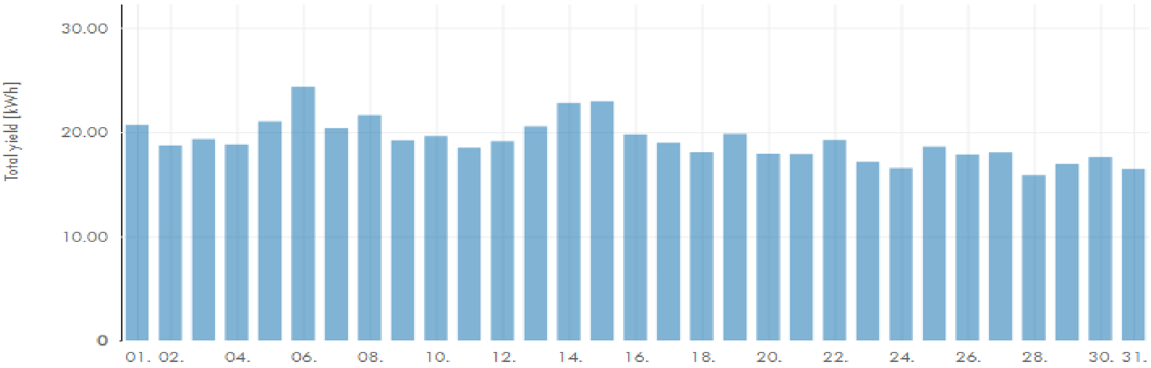


Figure 46: Daily Generation for August 2021

4.6.3.3 Battery health

Battery state of charge and power flow for a typical day in July is shown in Figure 47, when the total generation is one of the highest. From midnight to sunrise, state of charge steadily decreases as night time loads are used, revealing an unexpected finding that customers keep internal lights on all night. From sunrise, state of charge increases reaching full capacity by 11am. Recurring ‘bumps’ of direct consumption from the PV are observed during the day, and are caused by the air conditioner within the battery room cycling to maintain a steady temperature. Some additional daytime power is used by productive uses within the community, but are minimal. By sunset domestic lighting loads are seen to increase as the battery discharges steadily until morning. July also corresponds to harvest season when income levels (and associated electricity demand) of the community are highest. The battery bank being fully charged by mid-morning with low daytime consumption indicates significant excess generation capacity for additional daytime use, or bigger storage for night-time demand. It also demonstrates design estimates of night-time loads are correct, with the depth of discharge reaching the recommended limits of 80%.

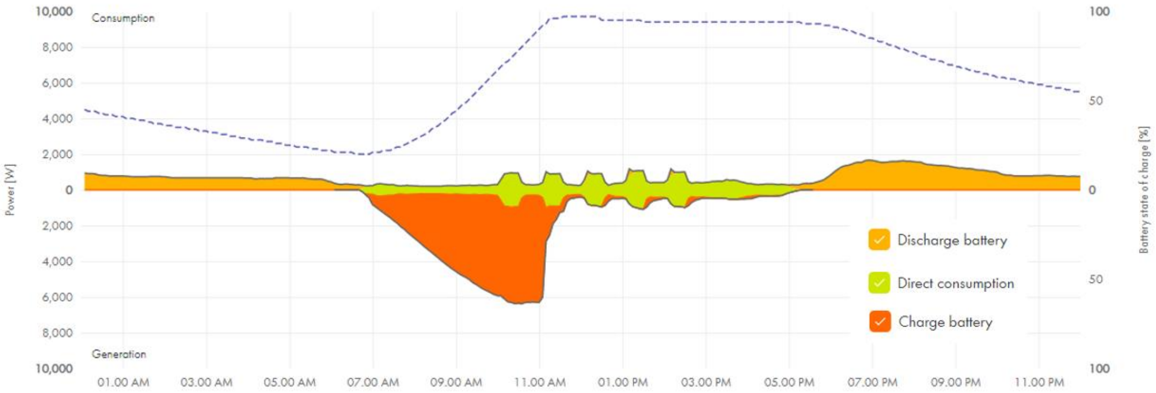


Figure 47 Battery state of charge and power drawn by battery, 10/7/21

This contrasts to Figure 48, a typical day in February, during the rainy season where cloud cover reduced PV generation but also corresponds to low incomes in the community and associated low electricity use. Cloud cover is observed through jagged spikes in the battery charging, and low demand reflected in the minimum battery state of charge of 55%, suggesting additional capacity can be utilised at night. Even at their minimum state of charge of 55% during the relatively low resource month of February, there remains a further 35% of spare battery capacity that can be used before the batteries reach their maximum depth of discharge of 80%. Despite cloudy conditions, the batteries are still fully charged before 11am, indicating significant daytime as well as night-time power available.

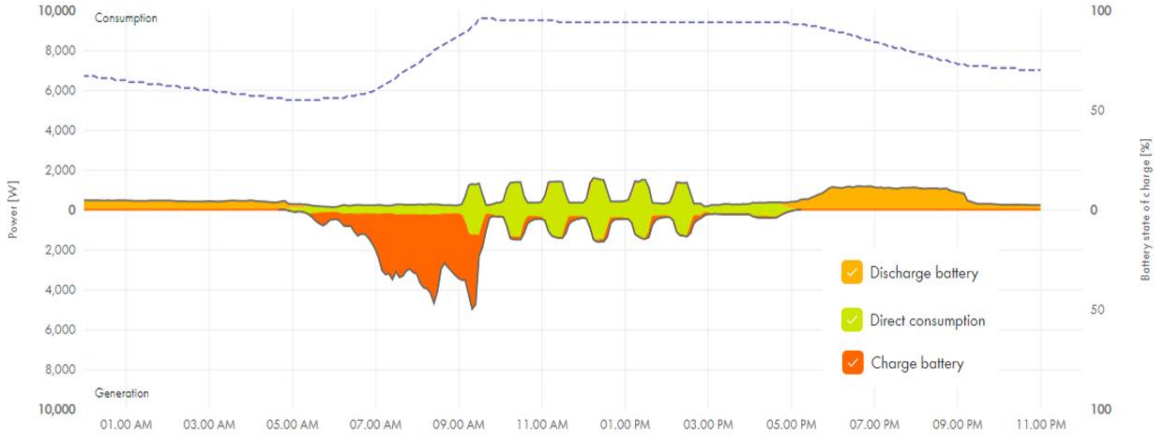


Figure 48 Battery state of charge and power drawn by battery, 13/02/21

Figure 49 shows weekly balance for a typical week (beginning 9th March 2021). Depending on weather conditions, the batteries reach full state of charge at different times, more cloudy days shown by a jagged rise, and a later time to reach full state of charge. On all days the battery state of charge remains in design constraints, never reaching maximum depth of discharge.

Figure 49 Battery state of charge and power drawn by battery, week beginning 09/03/21

Figure 50 shows the total monthly charge and discharge power experienced by the batteries over 2021, which follows similar patterns to the monthly power generation presented in Figure 45. This analysis can indicate issues in the battery, or trends of declining capacity to plan for battery replacement. As the first year of operation no issues are detected but insight such as this is essential for observing seasonal trends, monitoring battery health and adapting technical designs and tariffs accordingly.

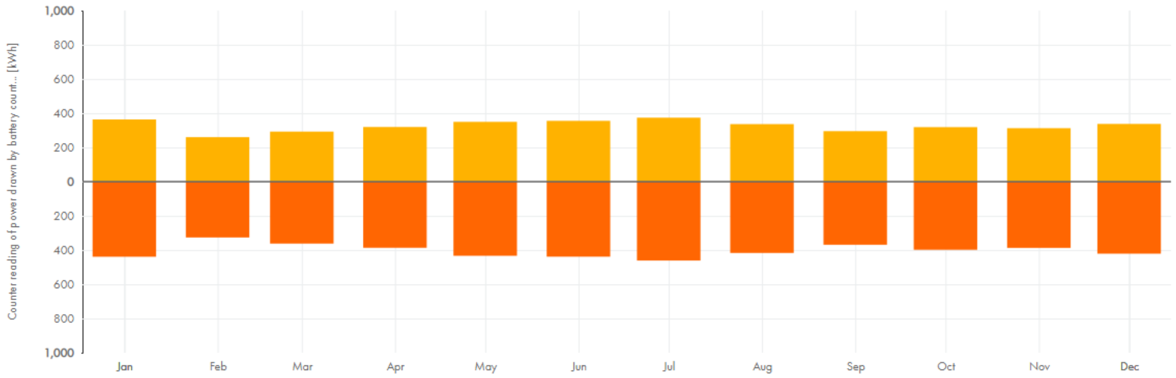


Figure 50 monthly total battery charge/discharge power (kWh) for 2021

Temperature logging revealed battery temperatures reaching over 35°C soon after the logger was installed in April 2022. High temperatures incur negative effects on the batteries health and lifetime. This occurrence happened when the air conditioning (AC) unit was being manually switched by the site agent. Following an alert sent to the site agent, the AC unit was switched on and the internal temperature reduced to 18 degrees. Actions were made to automate the operation of the AC unit to prevent a recurrence of high temperatures. Monitoring temperature in this way in order to identify high temperature and make adjustments in battery cooling has significant impact of battery lifetime, maintenance and OPEX costs and consequently associated project financials.

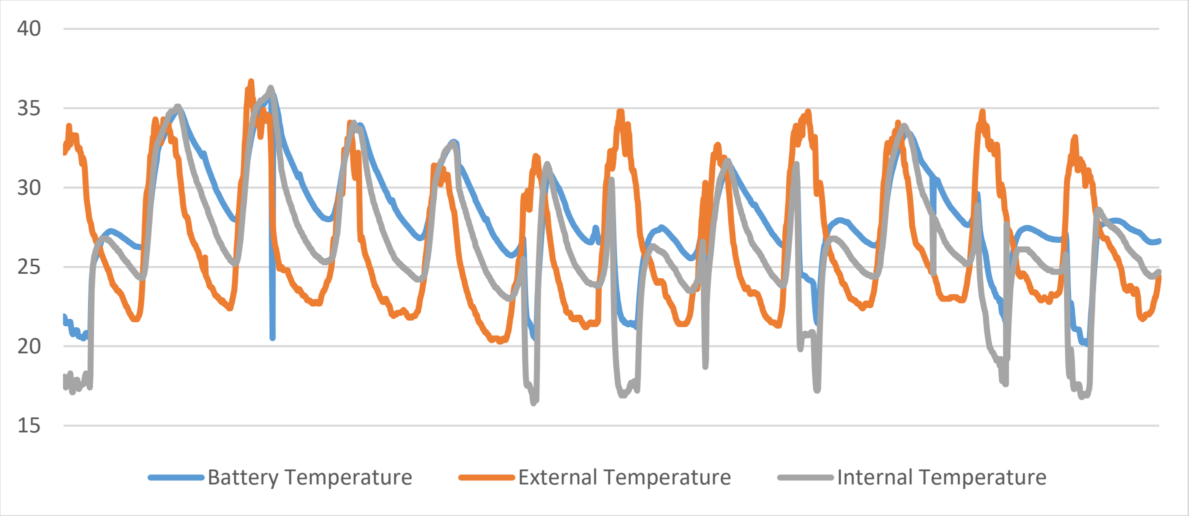


Figure 51: Battery Temperature, External Temperature and Internal Temperature, 10 minute intervals for 10 days in April 2022

4.6.3.4 Customer Segment Demand

Figure 52 shows total monthly demand for 2021, disaggregated by customer segment. Domestic customers have highest demand, ranging from 325 kWh to 350 kWh per month, with a seasonal trend that reduces in February's rainy season. The total business demand is lower, ranging from 65 kWh to 103 kWh, and is generally steadier. This contrasts with Figure 53, showing average monthly demand per customer for each customer segment, indicating business users have highest demand per customer (9-15 kWh). For both charts the institutional demand is low, demonstrating the low impact institutions have on technical performance and business models. This may change with the introduction of a health centre planned for connection. Understanding the breakdown of demand by customer segment demonstrates the higher demand from business customers and shows the impact promoting productive use of energy customers can have on utilization rate, as well as and informing design of seasonal tariffs intended to benefit customer segments accordingly. Analysing daily and weekly trends can give an even more nuanced view.

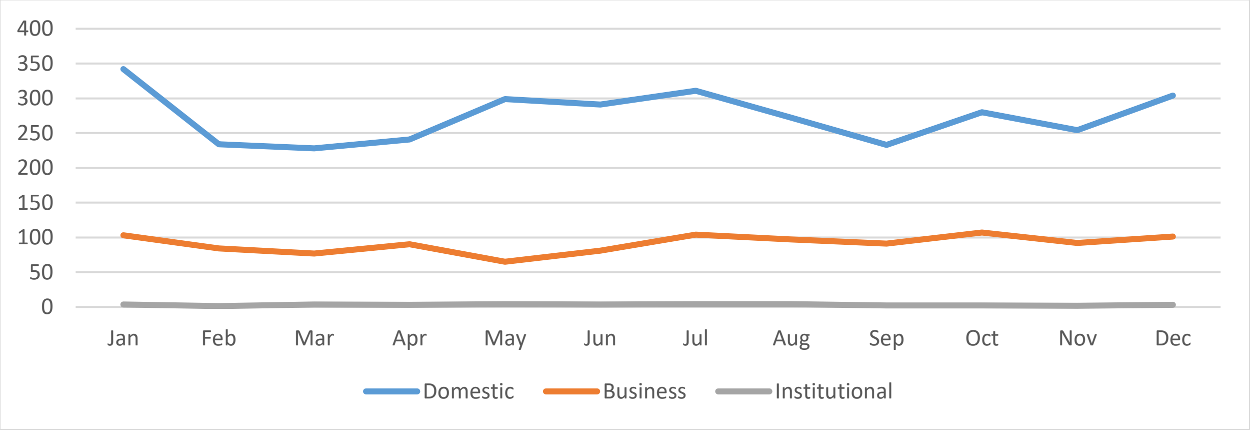


Figure 52: Total monthly demand for 2021 per customer segment (kWh)

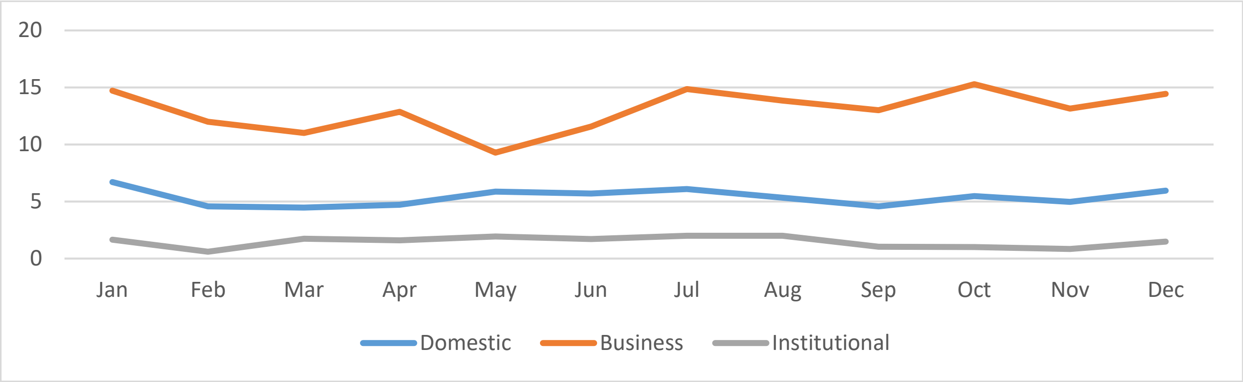


Figure 53 Average monthly demand per customer segment for 2021 (kWh)

Load profiles gathered from Steamaco data for total microgrid demand disaggregated into customer segments is shown in Figure 54, taken from analysis of hourly data (8760 data points) through 2021, including mean, median, 25th and 75th percentiles. The high proportion of residential customers is reflected in the high evening peak, with a second, more gradual daytime peak reached at 11am. The evening use tails off to a low at 4am, indicating customers keep their lights switched on until sunrise. Figure 55 shows customer segment load profiles, highlighting the higher demand and both daytime and evening peaks of business customers, and low demand of institutional customers. Understanding customer segment load profiles is key for targeted tariffs and mini-grid design.

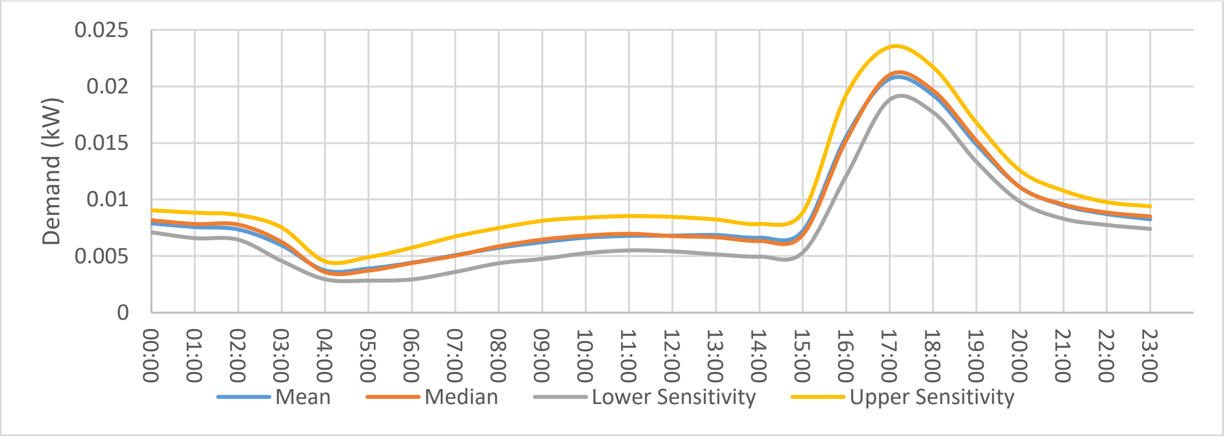


Figure 54: Average load profile for entire microgrid

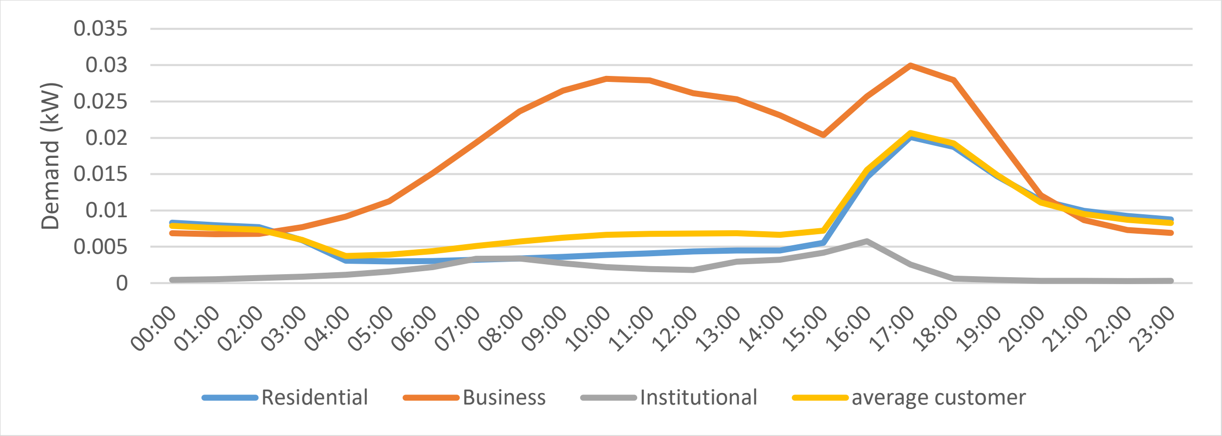


Figure 55 Customer segment mean load profiles

4.6.3.5 Utilisation Rate

Inputs and calculations for this process are summarised in Table 47, revealing a low utilisation rate of 21.6% and indicating that significant excess energy in the system is being wasted. A key challenge for any microgrid developer is to increase the utilisation rate in order to increase profitability and lower customer tariffs. The plan at Mthembanji is to address this by increasing daytime productive uses of energy in the agricultural value chain, specifically rice milling based on the presence of rice farming in the area. A pilot project implementing small (<2kW) rice milling machines have been identified for day time use. A keymaker model will be trialled, where the microgrid operator owns the milling equipment and offers a milling service to farmers, bringing in additional revenue to improve financials. Results from the pilot will be the subject of future research.

Table 47 Input Parameters for calculating utilisation factor

Parameter	Value
Location of the microgrid	-14.246680, 34.605612
Capacity of the generation	11.52 kW
System loss as a fraction	0.1
Tracking	none
Dataset	MERRA-2 (global)
Tilt	15 degrees
Azimuth	180 degrees
Annual theoretical yield	20, 461 kWh
Annual Demand	4,419 kWh
Utilisation Factor	21.6%

4.6.3.6 Technical discussion

The value of real time data access through remote monitoring and smart meters has been shown, with clear examples of technical KPIs informing operation and maintenance procedures, business modelling and future system sizing and design. Remote monitoring of the generation system specifically has been shown to be an essential tool for troubleshooting, gaining insight on system performance, and providing early warnings when issues are about to occur, all positively affecting system sustainability. As microgrid companies transition to operating larger fleets of microgrids, the need for tracking technical KPIs to inform robust asset management strategies leading to reduced levelized cost of energy from reduced lifetime costs and increased system availability and output becomes evident. While making this data more readily available to microgrid developers, more capacity building on the analysis and understanding of remote monitoring data is needed. The findings contribute to a growing body of evidence and advocacy toward enhanced understanding of microgrids through data capture and analysis [229] [194] [161], and case study technical analysis through remote monitoring [298] [299]

At Mthembanji, excessive downtime causing frequent customer blackouts has negatively impacted customer satisfaction and microgrid income. Mostly caused by poor mobile signal reducing smart meter functionality, the issues are a symptom of trailing novel technologies in new, remote environments. This finding corroborates the findings of [300], which states that "*deploying smart meters in rural areas can present additional challenges, such as the lack of reliable network infrastructure for data communication and the limited technical expertise of mini-grid operators*. At Mthembanji, resetting smart meter cores requires climbing equipment and specialist knowledge, necessitating a maintenance contractor's site visit from Lilongwe, increasing maintenance costs. Such costs could be mitigated through offering training to local site agents, avoiding transport and call out costs of a contractor. Although fault frequency is expected to reduce with mobile signal improvement and increased smart meter reliability through further product releases, in the short-term tracking and monitoring downtime is crucial to quantify impact on microgrid financials and customer satisfaction, and inform robust mitigation strategies.

Monitoring of battery health has provided valuable insight on microgrid technical performance and the impact of weather conditions on battery performance, while testing design assumptions. The importance of effective cooling strategies when housing batteries in shipping containers has also been demonstrated, highlighting the need for further research on cooling strategies and impact of temperature on battery lifetime. The impact of temperature on batteries in microgrids is a subject of current research [70] but the nascent sector has little data to inform understanding which these findings contribute to. Addressing the low utilisation factor of 21.6% should be a priority for the microgrid operator, as underutilised capacity is effectively wasted energy and revenue. Excess generation for solar microgrids typically occurs during the day, which can be addressed through promoting productive uses and tariffs designed to incentivise daytime use. Measured utilisation rates for active minigrids are scares, and significantly varied due to the multitude of different types of project. [293] benchmarking found a range utilisation rates for the minigrids they assessed of 5% to 75%, while [301] found a range of 2% to 100% with a median of 19%, indicating the findings are in line with Nigeria’s experiences. At Mthembanji, a 75% daytime discount was applied to encourage daytime use, but has not resulted in significant increase of the utilisation rate. Further barriers in access and affordability of PUE appliances such as mills and irrigation equipment must be overcome through appliance financing to fully address this, evidence which feeds into a growing body of understanding and advocacy around PUE on minigrids [294] [302] [179]. Load profiles and customer segment demand are of particular value and relevance to microgrid operators in Malawi, as insight on electricity use of previously unconnected communities is rare, and understanding daily and seasonal demand along with load growth over time is essential for optimising future microgrid technical and business designs. The load profiles presented here contributes to existing studies that aim to better understand demand of previously unconnected customers [248] [194] [161], an essential parameter to inform technical and business design.

The average monthly demand per customer for Mthembanji of 6.19 kWh corresponds almost exactly to the African mini-grids benchmarking study, which found from all the sites it assessed that *“the average consumption per customer is only 6.1 kWh per month across the continent”* [293] The load profiles show typical trends of a high residential load, corresponding to demand patterns found in [248], [303] and [304]. Along with promoting data sharing of pilot load profiles, further research comparing measured load profiles of specific customer segments to baseline surveys responses will provide more accuracy in predicting customer segment demand and already the topic of research in Tanzania [305].

4.6.4 Economic indicators

4.6.4.1 Sales revenue

Total monthly microgrid revenue from electricity sales for 2021 is shown in Figure 56, revealing a seasonal consumption peaking in July at 400 USD/month and reducing to 228 USD in March. Figure 57 shows Average Revenue per User (ARPU) following a similar trend ranging from 3.81 USD/month in February to 10.94 USD/month in July. The mean ARPU for the year is 5.43 USD/month , which is higher than estimates for Tanzania (USD 4.58), Kenya (USD 2.96) and Nigeria (USD 4.83) [293]. The data shows a seasonal correlation between microgrid revenue and customer ability to pay, which is associated with the harvest season of rice in the area. Such trends can be used to plan timings of appliance financing programmes or seasonal tariffs. Acknowledging the mean ARPU of businesses (USD 8.48) is more than double residential (USD 3.89), highlights the importance of increasing revenue through promotion of PUE through business support. Comparison of ARPU with monthly OPEX costs can be used to identify and quantify periods of revenue shortfall and surplus, which can in turn offer some insight to the financial sustainability and inform business planning. In the case of Mthembanji, the income only just covers the monthly OPEX costs, and provides no support for additional staff costs, transport, or wider business costs. This shortfall will need to be addressed to demonstrate a positive balance sheet to attract investment for scale.

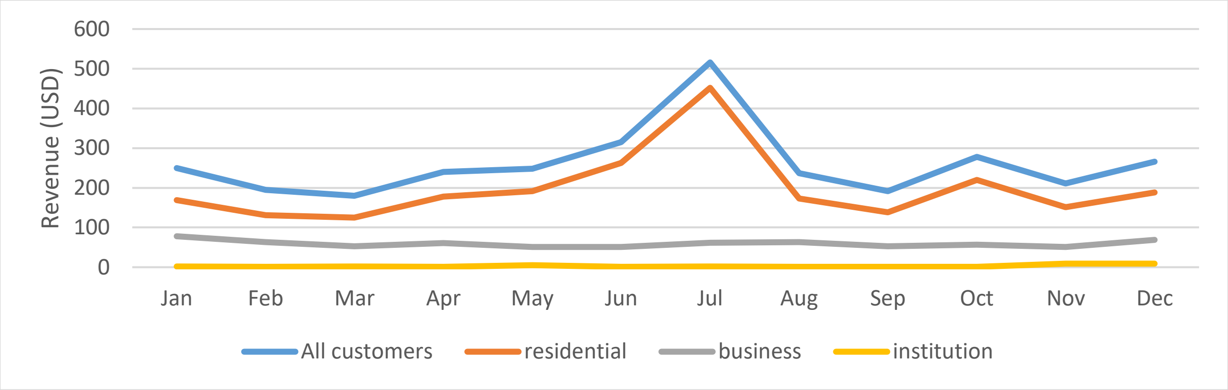


Figure 56 Customer disaggregated total revenue (USD), 2021, Mthembanji

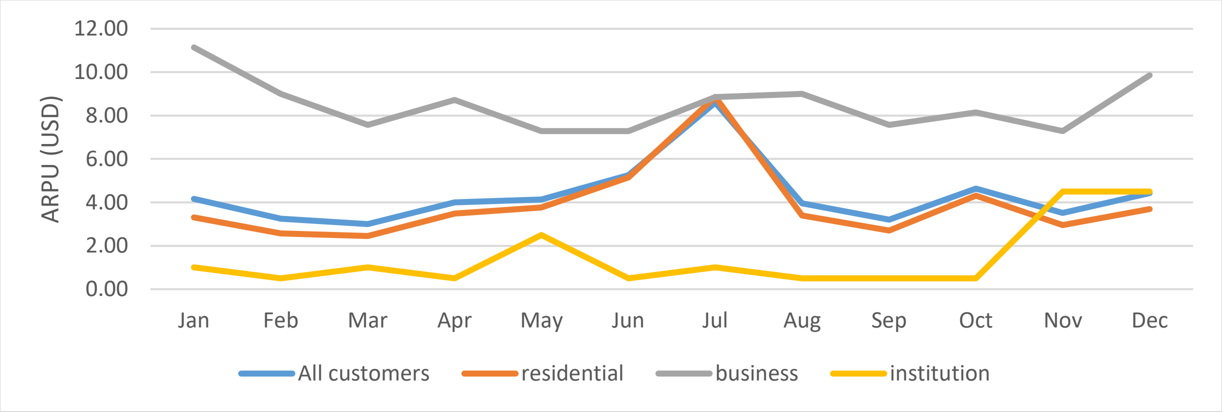


Figure 57 Customer disaggregated Average Revenue per user per month (USD), 2021, Mthembanji

4.6.4.2 Cost per connection, cost per kW and total cost of power

A summary of CAPEX costs is outlined in Table 48 of USD 1,700/connection and USD 8,869/kW are towards the higher end of current benchmark figures, with [293] stating that microgrid CAPEX cost in Sub-Saharan Africa currently range from 4,000 USD/kW to 11,000 USD/kW. Not included in these costs are development costs, including staff time for site prospecting, community engagement, fieldwork and technical design and project management, which were covered through EASE funding, but if not would have increased the CAPEX costs further. This KPI demonstrates the nascent nature of the microgrid market in Malawi and should continue to be tracked as further installations are deployed and cost reductions achieved through increasing economies of scale and system and project efficiency savings.

Table 48 Microgrid CAPEX summary

Item	Cost
Generation	$ 55,603
Distribution and smart meters	$ 27,968
Installation and fees	$ 18,425
Total	$ 101,995
Cost per connection	$ 1,700
Cost per kW	$ 8,869

Site based operational costs for 1 year logged through EASE project records outlined in Table 49 show a total of USD 316.4/month on average or USD 3,796.8/year, but do not include staff costs, transport costs and business overheads, provided through EASE grant funding. A monthly customer cost of 5.27 USD/consumer/month is already on the high side of bench mark estimates for SSA of USD 2.50 – 6.00 [293]. A comparison with monthly revenue (Figure 57) reveals revenue only just covering site-based costs, compromising financial sustainability without interventions on tariffs, demand or operational costs. The total demand of energy sold for 2021 is 6,369.29 kWh, which makes the cost of power excluding CAPEX and subsidies for the period in question as 0.6 USD/kWh. These KPIs are of key interest to investors and donors, and for tracking financial sustainability. Microgrid developers should be continually looking for ways to increase the kWh's sold and decrease the costs required to produce that electricity in order to provide affordable tariffs while maintaining sufficient income to ensure financial sustainability.

Table 49: OPEX costs

OPEX component	Month cost (USD)	Annual cost (USD)
Data for 3G router (16,800 MWK/m)	20.16	241.92
Steamaco SaaS Fee 0.54 USD per meter	32.4	388.8
Steamaco SMS fees (average)	23.84	286.08
Site agents – (2 x 50,000 MWK/m)	120	1440
Security Guard (50,000 MWK/m)	60	720
Generation and Distribution Maintenance (600,000 MWK/yr)	60	720
TOTAL SITE BASED OPEX COSTS	**316.4**	**3,796.8**
Cost per customer	**5.27**	**63.28**

4.6.4.3 Economic discussion

Capital costs provide a valuable data point in a grey market to inform investment, design and potential subsidy strategies in Malawi. The cost per kW installed of USD 8,869/kW is towards the higher end of current benchmark figures (4,000-11,000 USD/kW), while the cost per connection of USD 1,700/connection is higher than benchmarking ranges in Africa (733 - 1,555 USD/connection) [293]. Such high costs result largely from the nascent nature of the Malawian microgrid market. Lack of locally available components necessitates purchasing from abroad and increases transport costs, while lack of experienced installers further increases costs. This will likely change as more microgrids are installed, economies of scale can be reached and prices reduced. The project budget faced additional challenges with currency exchanges, lack of available foreign capital and inflation causing prices to fluctuate. These challenges demonstrate the need for project managers to allow for contingency in capital budgets, track exchange rates and incorporate back-up plans for volatile economic conditions. Policy makers can support the transition through strengthening supply chains, ensuring locally available microgrid components to reduce delays and ensure sufficient foreign capital for component purchasing.

The ARPU data provides valuable insight of rural customers' AWTP. The mean ARPU for the year is 5.43 USD/month, which is higher than other benchmarking estimates (USD 2.96 – USD 4.83 [293] and USD 5.00 [229]. The tariff was initially found to be too high by the community, resulting in complaints and negotiations conducted over time to find an acceptable tariff. Ongoing assessment of AWTP is essential for finding tariff sweet spots and ensuring customer satisfaction and sustainable levels of electricity consumption that avoids impoverishing communities further. Data sharing of ARPU and tariff levels between microgrid developers progresses the knowledgebase to informing sustainable business models with affordable tariffs, and the findings build on recent publications in this research area [214] [206]

OPEX costs were also found to be high, with ARPU only just covering site based operational costs without donor covered costs such as project management and transport. This mismatch is due to high operational expenditure, linked to challenges of reaching remote locations, and the need to trial unproved operational strategies, and low demand and low revenues, reflective of rural energy consumption across the board (including solar home systems, or grid connections). The measured OPEX costs of USD 5.27 per customer per month are towards the higher side of benchmarking figures in Africa (USD 2.50 – 6.00) [293]. For Mthembanji, the majority of OPEX costs come from a maintenance contract with a contractor, currently the only option in Malawi given the lack of technical capacity to conduct robust maintenance on microgrids. One way of reducing these costs is for an operator to have in-house maintenance technicians, with salaries paid through the central funds, and only transport/material costs needed for maintenance trips. Travel to different microgrid sites could be combined and efficient logistics strategies employed to reduce travel times and save on costs. The other way to address financial sustainability is to increase revenue through increased demand, either through increasing the number of customers or promoting daytime demand. At Mthembanji this is being addressed through implementation of rice milling operations at the site.

The high costs and vulnerabilities in matching expenditure with income from electricity sales demonstrates the need for smart subsidies [306], [307] to enable solar microgrids to scale. Subsidies for grid connected electricity supply in the Global North are universal, and asking the poorest communities to bear the full cost burden of electrification with no support is unstainable and unfair. Through data sharing of costs and income between multiple active microgrid projects, a case can be made to government based on a quantification of the subsidy required, and the evidence presented here contributes to a growing academic advocacy for targeted mini-grid subsidies [308] [309] [310]

4.6.5 Social impact indicators

4.6.5.1 Demographics

Table 50 shows the microgrid serves 335 people (reduced from 346 in the baseline survey), with an average household size of around 6 and a maximum household size of 12 throughout the surveys, comparable to the average household size in SSA of 6.9 [311]. The number of female-headed houses has remained low at 4. Figure 58 shows the number of people in households disaggregated by gender and age, indicating a large youth population with ages 7 – 17 being the highest for each survey.

Table 50 Household demographics

	Baseline	**Survey 1**	**Survey 2**
Total people in household	346	335	335
Average household size	6.29	5.98	6.09
Max household size	12	10	12
Number of female headed houses	4	4	4

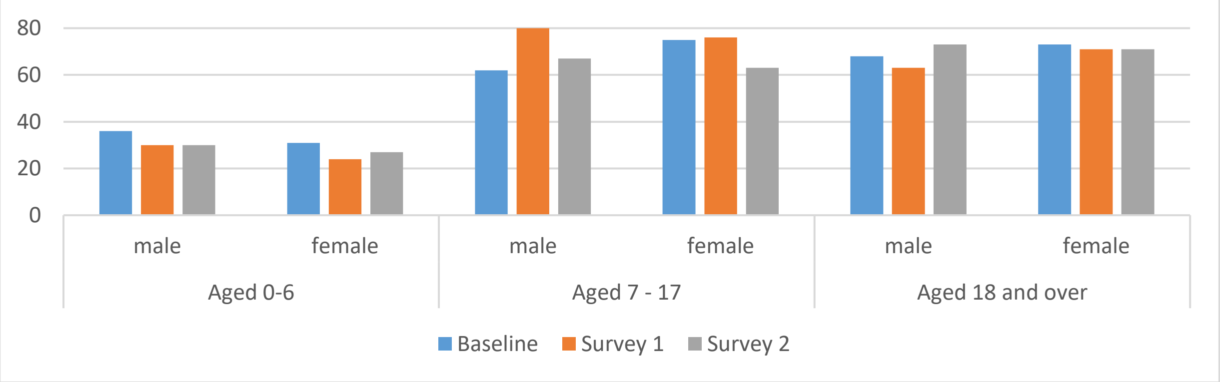


Figure 58 number of people in houses with a connection disaggregated by gender and age

Gender disaggregated education levels as reported in the baseline survey are shown in Figure 59, which have not changed in subsequent surveys. The majority of customers have completed primary school, with 24% completing secondary school, 8% pursuing higher education, and 11% having no formal education. Understanding education levels aids in gauging technical positioning of community engagement, and tracking over long time periods aids understanding microgrid impact on education. According to baseline household occupations, the majority of customers are farmers, with some running grocery stores or brewing, and some teachers. Follow-up surveys ask if anyone in the household's occupation has changed, and on both surveys this is answered negatively, with the exception of one who indicated they were also running a side business.

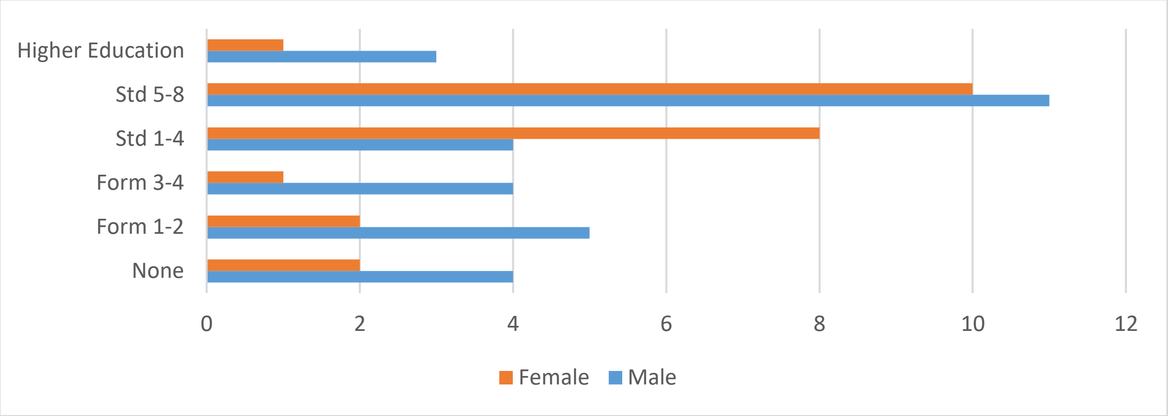


Figure 59 Education Level of survey respondent disaggregated by gender (baseline)

Tracking demographic indicators on baseline and over time reveals how many people are experiencing the social impact described in subsequent indicators, and who these people are. Understanding gendered education and employment levels aids in gauging technical positioning of community engagement, and tracking over long time periods aids understanding microgrid impact in these themes.

4.6.5.2 Energy access

The number of customers has remained at 60, leaving the potential unconnected customers at 127 and the percentage of the community connected remaining at approximately 32%. Figure 60 depicts how energy device use has changed since installation, indicating all non-microgrid devices, including PSP, SHS, 12V Battery, and dry-cell battery use, have decreased since microgrid use. This impacts many aspects of community life, including reduced environmental impact and pollution. Dry-cell battery reductions in particular will benefit the environment as batteries are rarely recycled and leak acid into the soil, they also have a significantly higher cost/kWh than the microgrid. The evolution of lighting device use since installation is shown in Figure 61. As microgrid lighting became the primary lighting source for 100% of domestic customers, the use of solar home lighting and single charge torches decreased as expected. Phone torch use first reduced then increased, follow-up surveys would determine whether the microgrid lighting is adequate or if additional lighting devices are required. Customers are currently offered four internal and one external lights. Figure 62 depicts appliance use since installation, indicating an increase in the use of stereos and televisions, a decrease in the use of radios, computers, and other appliances, and no change in the use of refrigerators. This data will inform community engagement and future appliance financing schemes on the site. Figure 63 shows the results of the likert question “How satisfied are you with your access to energy?”, showing over time an increase of “very happy” and decrease of “very unhappy” responses. Contrary results should highlight issues with the service and be investigated for rectification.

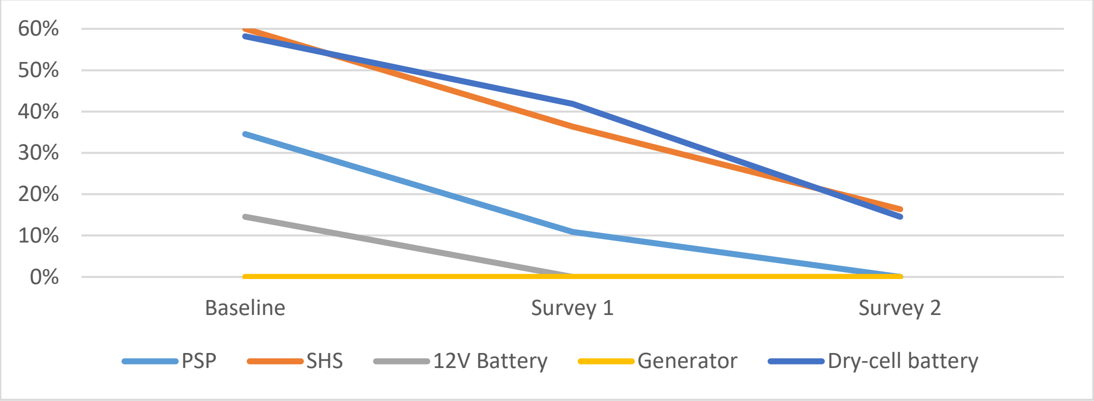


Figure 60 Energy Devices

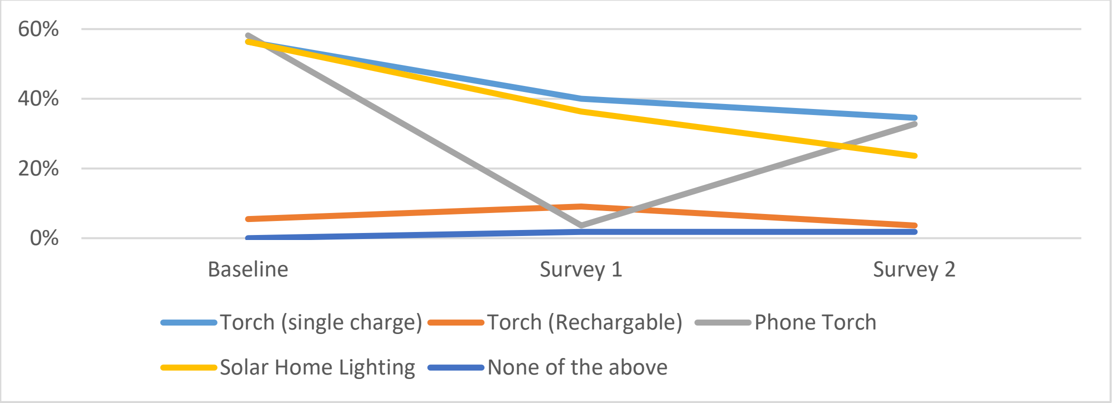


Figure 61 Lighting Devices

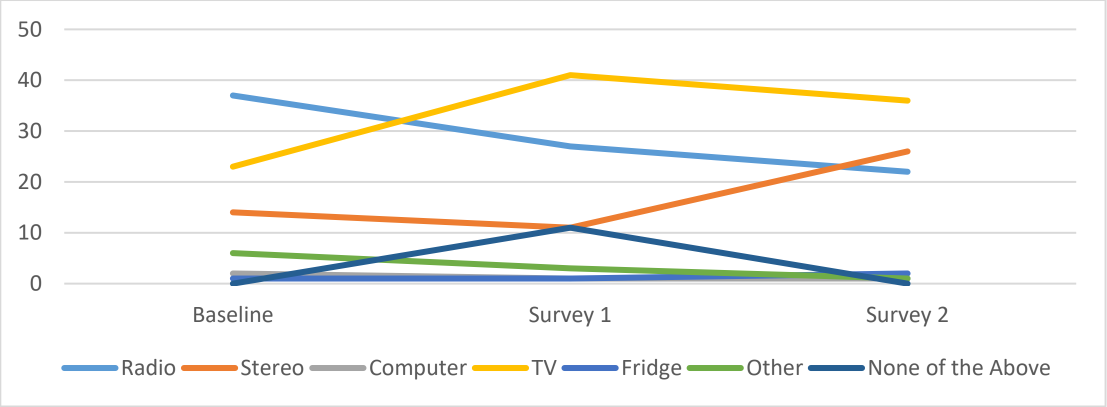


Figure 62: Appliance use

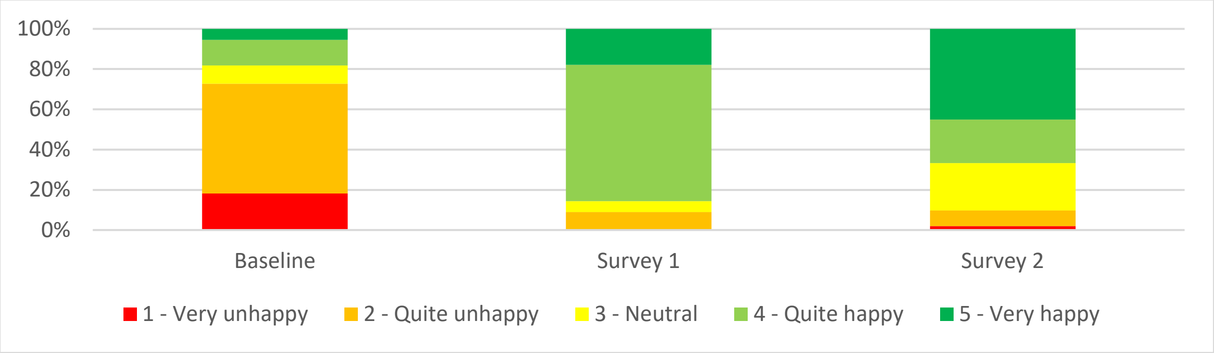


Figure 63 Satisfaction with Access to Energy

4.6.5.3 Health, education and communication

The number of health centres or hospitals has remained at 0, although a newly establish health clinic will be connected when the system is expanded. The number of burns or injuries reported related to cooking, heating or lighting. This was reported as 4 in the baseline, increasing to 5 and then 7 in survey two. Positive impact in this KPI is not expected until the microgrid powers eCook devices. 40% of customers indicated access to health information has 'very much improved' or somewhat improved, shown in Figure 64.

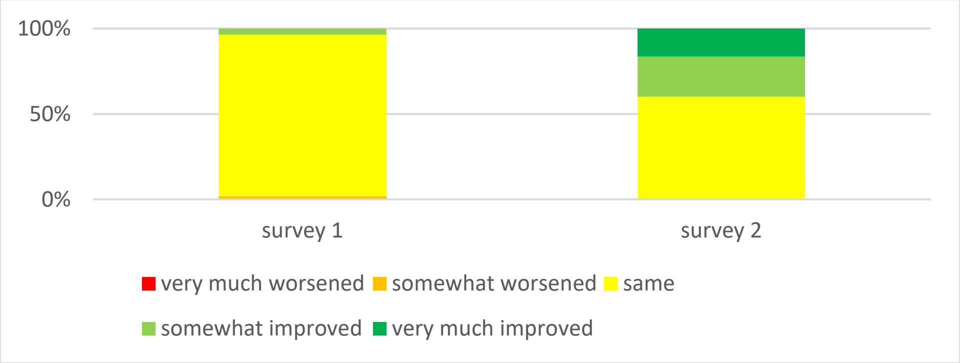


Figure 64 Access to health information

The number of schools connected with access to ICT has remained at 1. The percentage of households reporting that children study at home has reduced from 92% in the baseline to 89% in Survey 1 and 79% in survey two, however study sessions are also conducted at school after dark, and children whose homes are not connected to the microgrid benefit from this arrangement. Figure 65 shows the average number of hours spent studying in the home, which indicates a reduction from 4.06 to 3.88 between baseline and survey one, followed by an increase to 4.31 in survey two. This suggests that children are spending more additional time studying in the home since installation, further surveys or interviews with customers would be required to make a clear contribution to this from the microgrid.

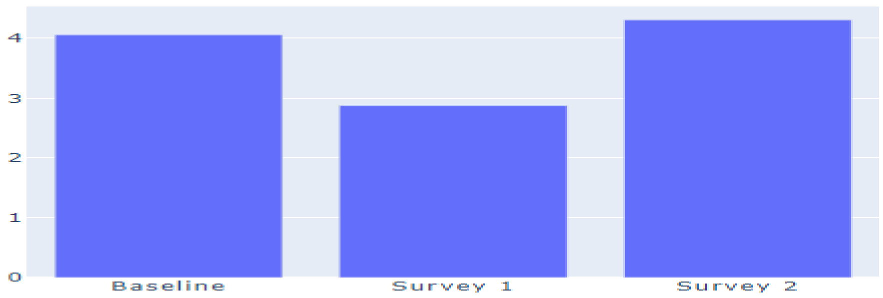


Figure 65: Average number of hours spend studying in the home

The community's access to local and national news since installation is summarised in Figure 66. Daily news access has reduced between baseline to survey 2, while several times per day access to news has increased over time. Analysis of the KPIs over longer time frames will contribute to an understanding of how access to energy impacts communication and connection to the wider world.

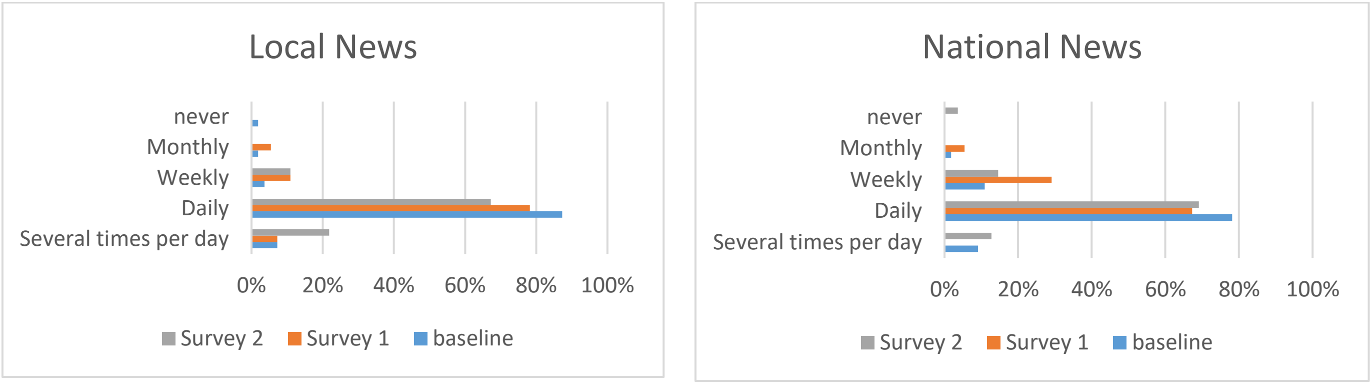


Figure 66: Access to local and international news

Figure 67 shows the number of mobile phones and smart phones owned by microgrid customers, indicating an increase in total phone ownership, with an increasing proportion of smart phones. Customer satisfaction with smart phones since installation is shown in Figure 68, which demonstrates a general trend of increased satisfaction over time. The microgrid offers in house phone charging for all customers and tracking phone ownership and associated satisfaction is an indicator of how the microgrid contributes to social impact in terms of increased connectivity.

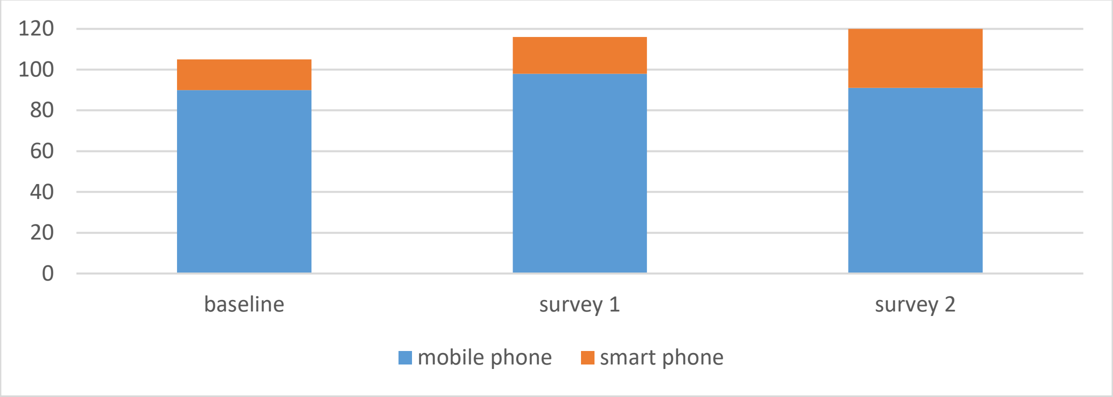


Figure 67 Mobile phone and smart phone ownership

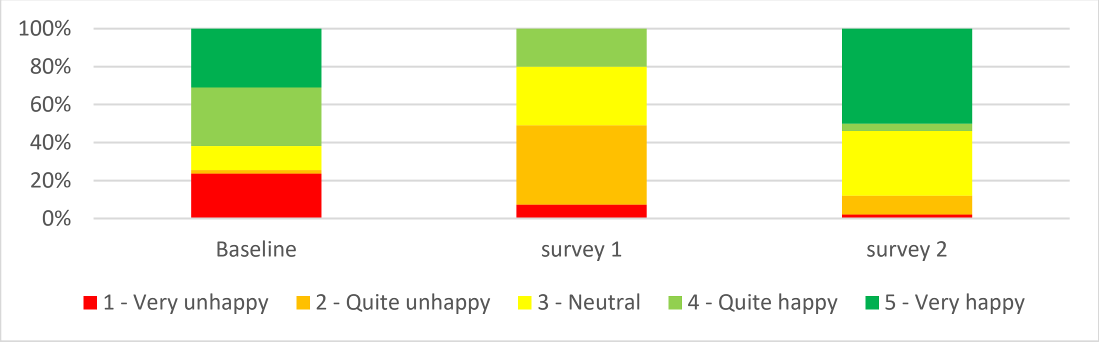


Figure 68 Satisfaction with access to smart phones

4.6.5.4 Employment, finance and PUE

Mean monthly income and expenditure is shown in Figure 69 and Figure 70. As income is highly volatile, questions ask for estimates of the highest and lowest monthly income and expenditures, although expenditures were not asked for the baseline. The data suggest a decrease in both income and expenditure between baseline and survey 1, followed by an increase in both between survey 1 and survey 2. Asking income figures directly through surveys is inherently difficult [312] as finances follow seasonal trends, records generally are not kept, and few are on set contract with steady monthly incomes. This is reflected by 24 customers in Survey 1 and 32 for survey 2 stating ‘don’t know’ for all responses.

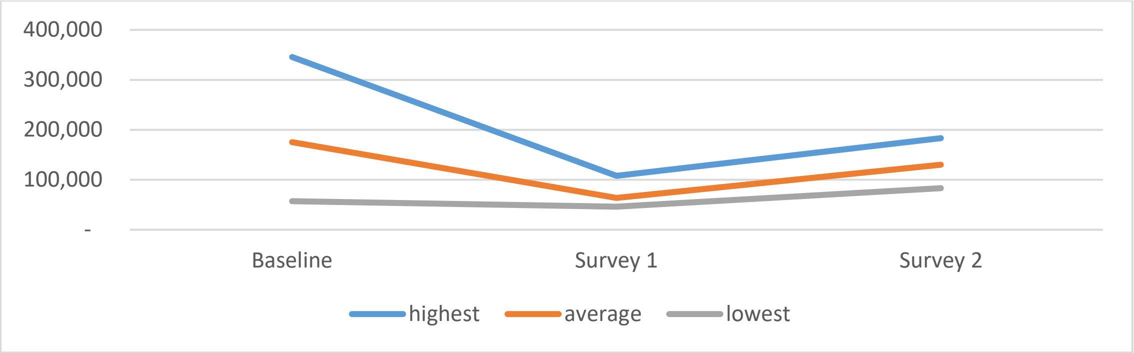


Figure 69 Mean monthly income levels stated by respondents (MWK)

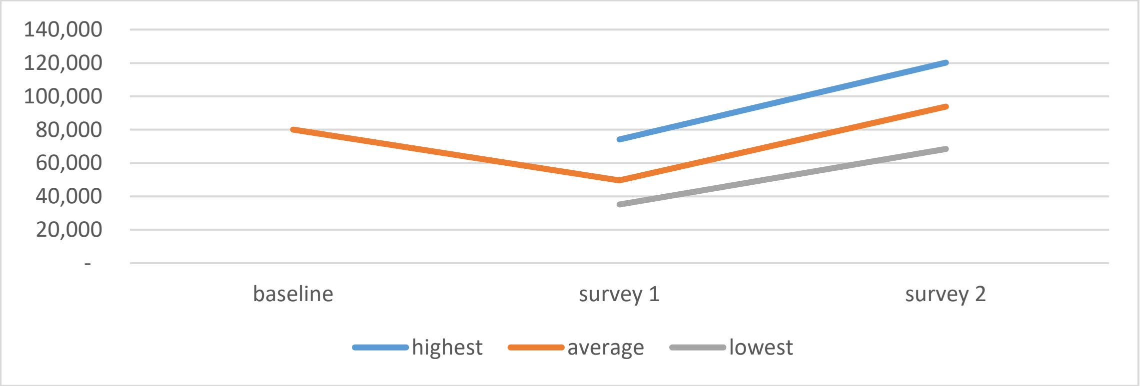


Figure 70 Mean monthly expenditure (MWK)

Figure 71 shows the number of businesses connected to the microgrid since installation, which has increased from 2 at the baseline survey to 14 in March 2022. Types of new businesses reported include: video show, grocery and liquor shops with fridges, computer cafés, cold soft drinks, saloons and barbershops. Two types of survey were used, one for business only properties (where nobody lives at the property), and one for businesses run from a residential property. The 'business only' connections has remained at 2, indicating the above rise in businesses are all 'household businesses'. Tracking new businesses is essential for predicting load profiles and modelling microgrid future revenue.

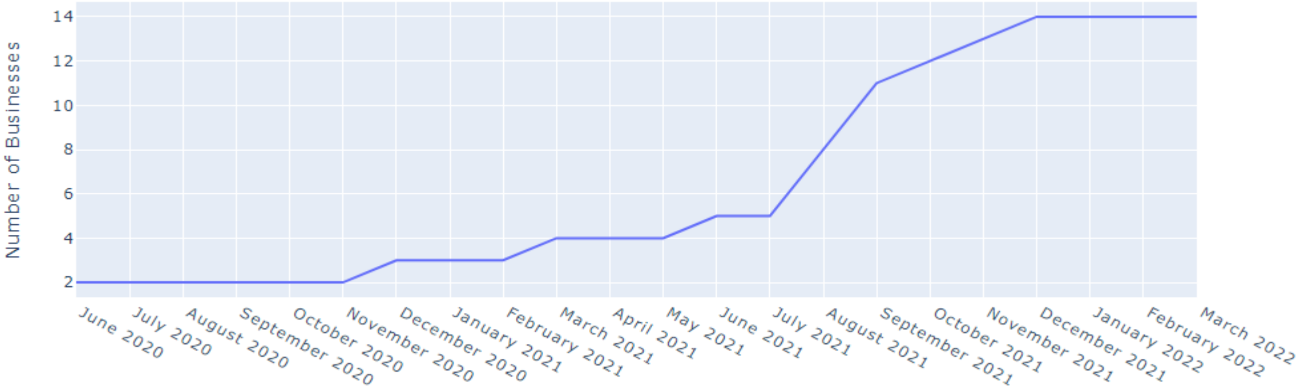


Figure 71 Number of businesses and industries connected

Business income and expenditure is shown in Figure 72 for business only customers, and Figure 73 for household businesses. All charts reveal an increase in both income and expenditure. Caveats to this data should the low sample number for business only properties (2) both stating they do not know their expenditure in survey 1, hence the lack of data. The number of paid employees was stated as 0 for both baseline and survey 2, rising to three for survey 2.

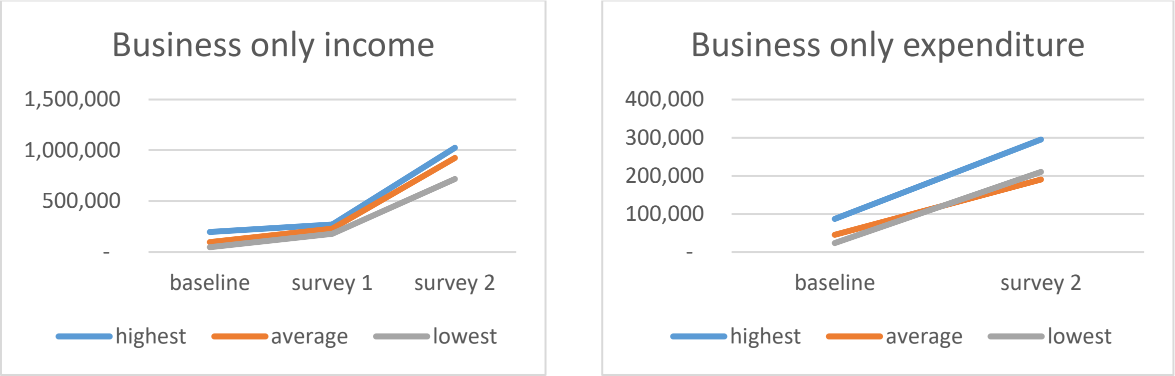


Figure 72 Business only income and expenditure

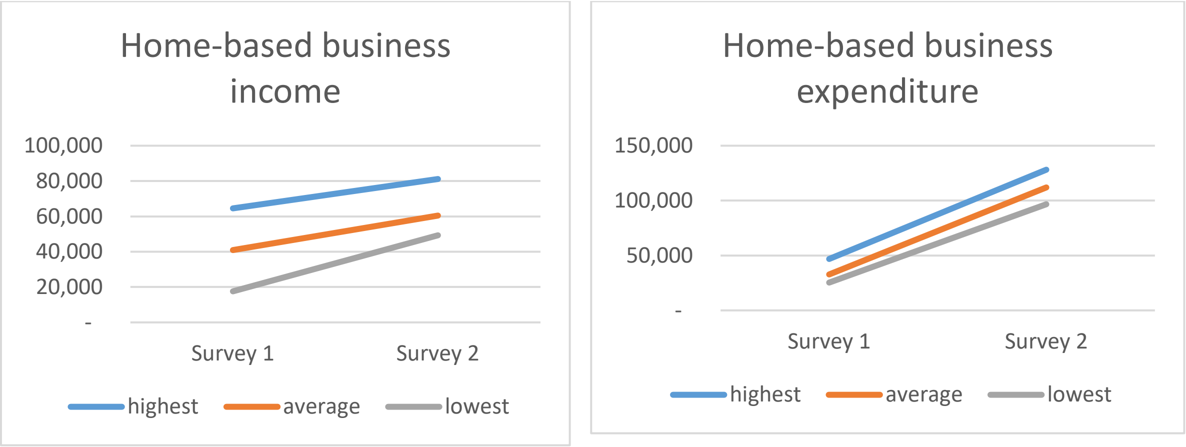


Figure 73 Home based business income and expenditure (MWK)

Perception of financial security corresponds to tariff satisfaction resulting from tariff adjustments made between surveys, as demonstrated in Figure 74. The percent of customers feeling very insecure or quite insecure increased from 51% in the baseline to 77% survey 1, then reduced to 38% in survey 2, possibly reflecting the tariff changes made between survey 1 and survey 2. Overall, the percentage of customers stating 'quite secure' or 'very secure' has steady reduced over the course of the surveys from 40% to 13%, noting that the financial well-being of the community is subject to several external influencing factors. Satisfaction with employment status is show in Figure 75, showing an increase in 'quite unhappy' and 'very unhappy' responses from baseline to survey 1 (23% to 62%), followed by a decrease of the same to 18% in survey 2, and an increase of 'very happy' responses between Survey 1 and Survey 2 from 2% to 24% . These general trends of satisfaction decreasing between baseline to survey 1 and increasing to survey 2 may be due to seasonal trends, as well as the tariff adjustments made.

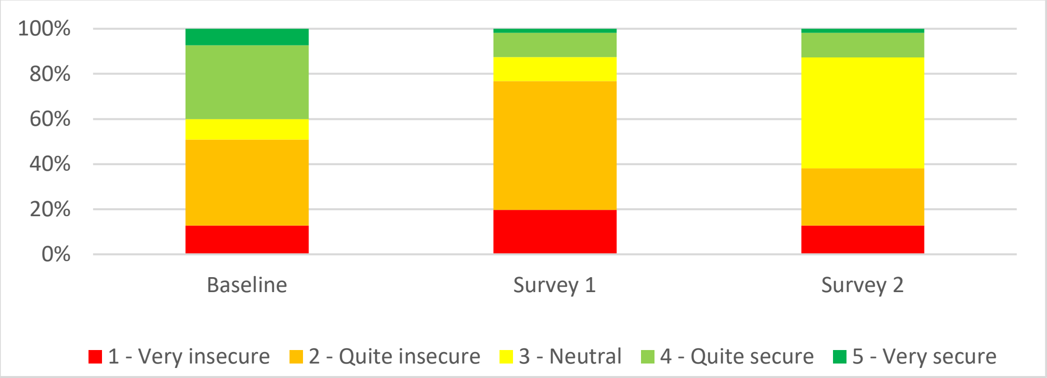


Figure 74 Perception of household financial security

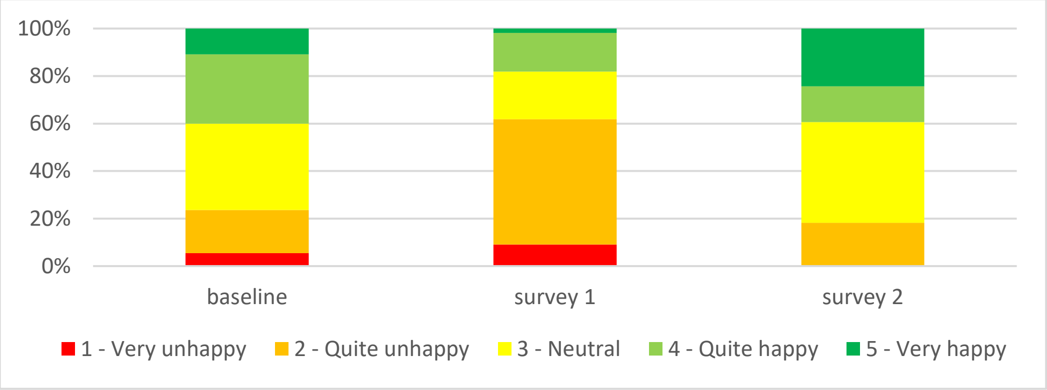
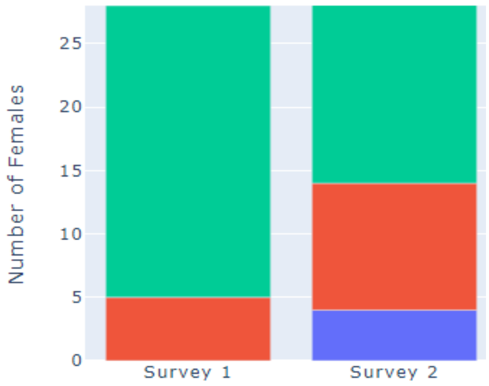


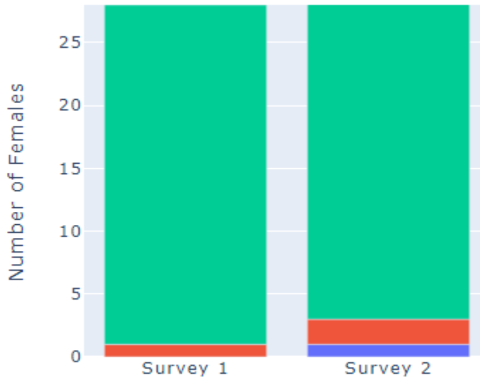
Figure 75 Satisfaction with employment status

4.6.5.5 Female empowerment

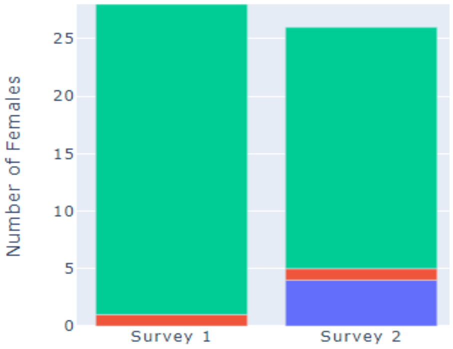
The number of women and girls with access to electricity is 164, or 49% of all people in connected households. The number of female owned businesses is 3. Figure 76 shows the results for the two surveys on female empowerment KPIs. The data suggests positive impacts on amount of free time, independence and decision making, respect within the community and household, and security in the home. The biggest changes are seen in security in the home.



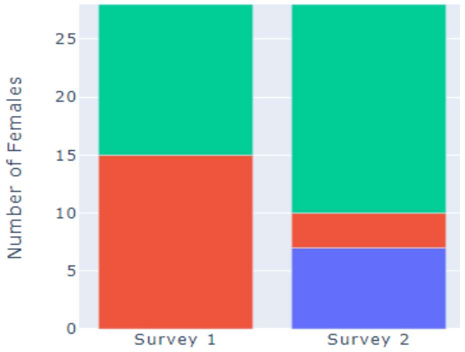
Amount of free time



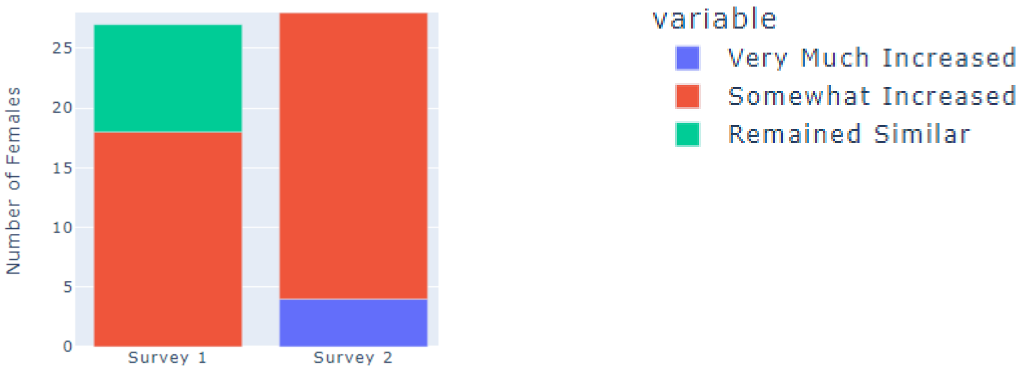
Independence and decision making



Respect within the household



Respect within the community



Security in the home

Figure 76 Female Empowerment KPI tracking

4.6.5.6 Tariff and service

In terms of financial satisfaction with the microgrid, Figure 77 displays how satisfied the users are with how much they are paying for their electricity. The general satisfaction has increased from survey 1 to survey 2, reflecting the tariff reduction during this period and an associated increase in willingness to pay. Figure 78 shows payment method satisfaction, indicating an increase in 'very happy' from survey one to survey 2, although a few customers being 'very unhappy'. According to field staff, payment through site agents has generally been a success although if top-ups are needed outside of work hours, customers suffer. This indicator informs the impact and satisfaction of new tariff payment methods such as mobile money integration. The electricity spend comparison, calculated as the average of current spend minus ideal monthly spend is 2.26 USD for survey 1 increasing slightly to 2.29 USD for survey 2, corresponding to 43% and 44% of the monthly ARPU for 2021, suggesting the customers willingness to pay is still lower than the current tariffs.

Value for money responses are shown in Figure 79, indicating over 50% of customers still regarding the microgrid bad or very bad value for money, although some customers have begun to indicate it is good or very good value by survey 2. Regarding perception of payments being a burden, Survey 1 revealed 14 % indicating payments were ‘a burden’ and 1 customer said they were a ‘heavy burden’. By survey 2 this had reduced to 9% indicating it was ‘a burden’ and no customers reporting ‘a heavy burden’. This question is designed to confirm that microgrid complies with the international development ethos of “do no harm”, where it is essential that microgrid developers avoid exacerbating rural poverty, by pushing rural customers deeper into it through a high cost of electricity.

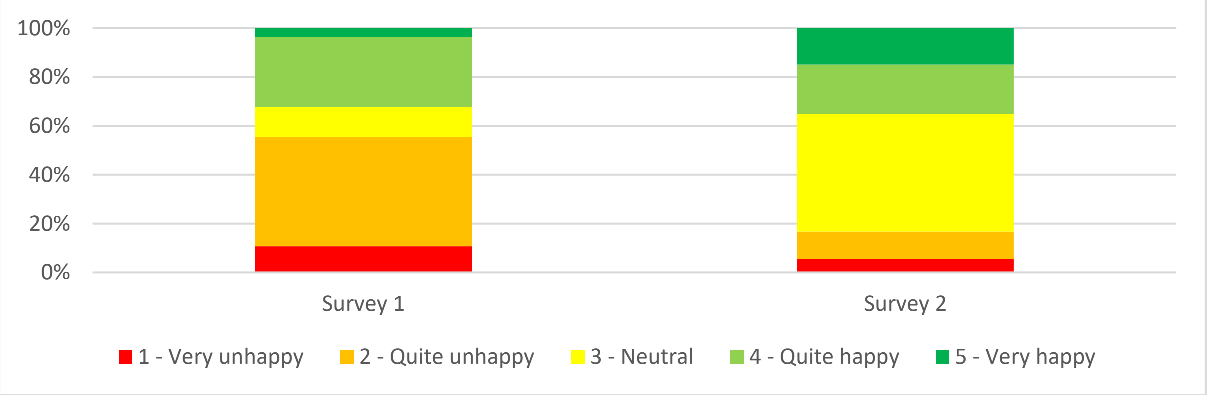


Figure 77 Tariff Price Satisfaction

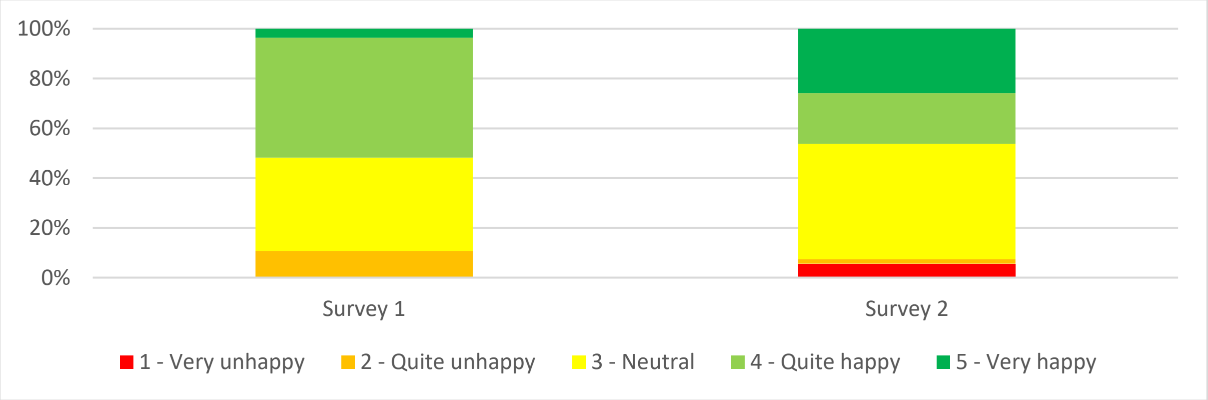


Figure 78 Payment method satisfaction

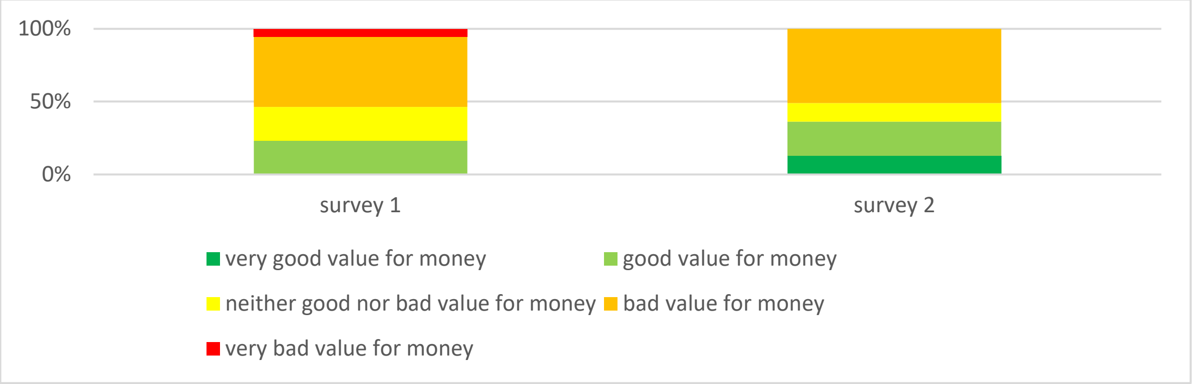


Figure 79 Value for money

Responses to the "To what extent has the quality of life of you and your household changed since getting the connection?" (Figure 80) shows that by Survey 2, 80% of respondents stated ‘very much improved’ with a further 29% reported ‘somewhat improved’. Figure 81 shows a similar trend of increased perception of safety, with over 80% of respondents indicating they feel ‘somewhat safer’ or ‘much safer’ in both surveys, with the proportion of ‘much safer’ increasing to 64% by survey 2.

28% or respondents to Survey 1 indicated that there were negative consequences of the microgrid, with most comments relating to the electricity being expensive, limited number of lights, and its failure to meet their expectations and satisfy all of their energy needs, and also including some complaints focused on system outages and down time. In Survey 2 this had reduced to 15%, with less mentions of expensive electricity and more complaints on the grid outages, reflecting the issues experienced with the SteamaCo meters.

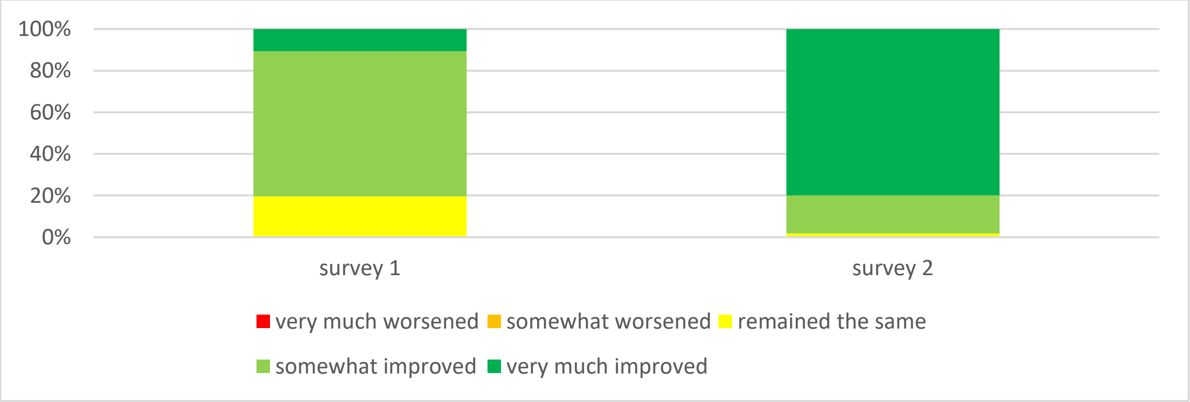


Figure 80 Change in quality of life

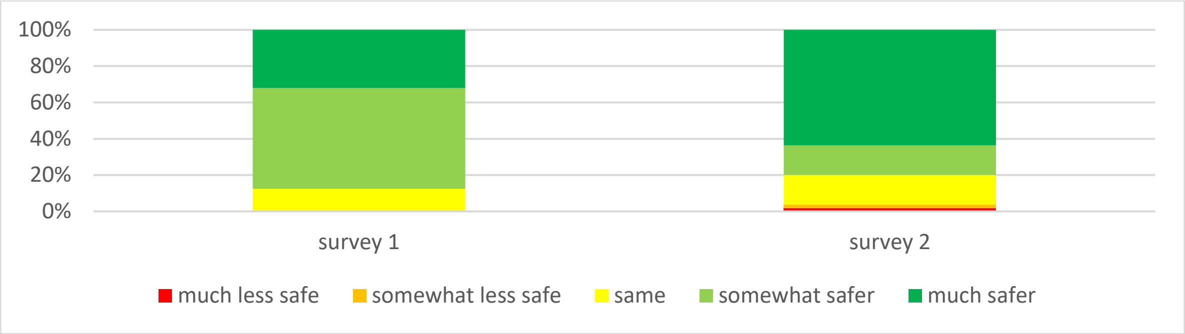


Figure 81 Perception of safety

4.6.5.7 Social impact discussion

Tracking social impact offers value in assessing the microgrids effect of achieving multiple SDGs, and offers a more nuanced and holistic view of the microgrid performance than just economic and technical metrics. Microgrid financial sustainability relies on satisfied customers that clearly benefit from the electricity offered through the microgrid, as well as a demonstration of the social impact experienced to investors and donors. Accordingly, a clear understanding of the social impact KPIs proposed helps to inform interventions in a SMSE business model to increase customer satisfaction, improve revenue and demonstrate impact to investors.

The household profile is critical for understanding customer segments and types of customers who use microgrid electricity in order to inform community engagement efforts such as tailored training or promoting specific appliances. Additional research could disaggregate demand based on household demographics such as family size, gender, and so on. When surveys are conducted for future sites, the demographics can be compared to data from previous microgrids to predict microgrid revenue and inform likely energy use.

Energy Access metrics tracking SDG7 contribute to national targets, and understanding lighting and appliance use inform business models through deeper understanding of demand, and is critical for predicting load profiles and advising appliance financing schemes. The low percentage of households connected in Mthembanji is ultimately due to budget constraints within EASE, and was a suspected contributing factor to vandalism of the system in 2022. Field staff speculated that damage was caused by unconnected community members with resentment towards community members with access to the microgrid. As connected customers were those able to afford the connection fee, this represents a potential widening of inequality within the community, a finding backed up by [260] whose assessment of multiple African minigrid and energy access initiatives revealed that "*the poorest customers still have less access than their wealthier peers*". This highlights the importance of an SMSE striving to connecting all members of the community that want a connection (regardless of economic status), and tracking progress towards this aim. The findings of microgrid customers utilising lighting as a primary energy service correspond with several studies evaluating the use and impact of minigrids [143] [313] [314] and rural electrification [315] [316]more widely. However, the findings of what lighting devices the microgrid displaces (primarily dry cell batteries) is contrary to other studies in East Africa, where Kerosene is more common starting lighting source [143]. The use of appliances including fridges, TVs and stereos correspond with other studies in Africa [237], [314] [143] as well as some in Asia, with a notable difference that use of fans aren't reported unlike studies in India and Nepal [145] [317].

Although a positive impact on health, education and communication is implied through the indicators measures, direct attribution is difficult to make and more robust social science research will further demonstrate linkages between access to energy and human development. This challenge of attribution is commonly stated in academic literature [314] [315] [131]as is the case study analysis of perceived positive impacts on health [145], education [134] [260] [142]and communication [142]. Some studies [314] [134] have explored the attribution of electricity supply to impacts on health and education through stakeholder (e.g. headmasters) and customer interviews, a method that would improve the rigour of this thesis. The experiences at Mthembanji have highlighted the need for continued and well-planned community engagement, from before the microgrid is installed, to regular engagement throughout the project cycle. In addition, providing electricity to communities where none has existed before, requires detailed training on safe use to avoid injury. At Mthembanji, customers were trained before connection on the basics of electricity, safety considerations and appliance use, with follow-up sessions conducted periodically.

Regarding impact on finances, the increase in number of businesses is a clear indication of increased local economic development, and customer perception of financial security has increased. This finding corresponds to other microgrid case studies stating an increase in number of businesses following electrification [143] [142] [260]. At this early stage it is challenging to attribute impact on household finances from the microgrid, especially as both income and expenditures of rural farmers is affected by a multitude of other influencing factors, including climatic conditions and macro-economics. Some minigrid case studies have identified monetary gains achieved through minigrid connections [145], with [134] finding that income levels of businesses in Kenya increased in the order of 20–70% when connected to a minigrid. A quantification of this type for the Malawi minigrid would be valuable for policy advocacy. Gaining an understanding of income and expenditure trends provides insight on positive economic impact though increased PUE and potential negative impacts through increased expenditure on microgrid energy increasing poverty, both essential to inform community engagement and business strategies.

Perceptions of impact on female empowerment appear generally positive, although the changes may be marginal. The findings of energy access improving the lives of women correspond with industry impact reports [145] [260], with specific validation found in literature on increases in safety [314] and availability of free time [133]. More detailed expert analysis involving detailed interviews and focus group discussions is required to fully understand the attribution impact on female members of the community. Tracking microgrid impact on female customers is a requirement for most social impact investors and a necessary activity for energy service social enterprises wishing to demonstrate gender impact.

Tracking customer satisfaction of pricing revealed customers generally unhappy with the cost of electricity, and tariffs still high compared to willingness to pay, a common problem with minigrids and energy access initiatives in general in Africa [260] [143] [318]. Affordability is a key pillar of SDG7 and allowing customers to consume electricity in a manner that benefits them economically is essential to achieve financial sustainability. Tracking progress on these indicators contributes to understanding ability and willingness to pay for electricity and is key to finding tariffs that foster demand without pushing communities deeper into poverty.

Understanding socio-economic impacts provided from microgrids is a complex topic. Microgrid developers should understand that achieving positive social impact goes beyond the provision of an electricity connection, but requires investment in resources for community support and engagement, including for example, PUE training, appliance financing, health and safety, and gender focused engagement.

4.7 Chapter summary

This chapter has assessed a SMSE though analysis of primary case study data, by following the methodology steps outlined in the previous chapter. An overview of the Malawian solar microgrid sector has been given, located within the wider context of energy access initiatives and progress in Malawi, and a summary of the pilot project through which data collection occurred has been provided. The methodology steps proposed in chapter 3 have then been followed utilising primary case study data, firstly to assessing the financial sustainability of a SMSE by conducting a use case feasibility study, carrying out a market assessment and conducting business modelling for scale-up. The novel social impact focussed KPI framework has then been utilised to assess the impact and performance of a pilot microgrid using 1 year's worth of data. A discussion section has commented on the implications of the results presented relevant to each step of feasibility assessment. In chapter 5 the conclusions of the study are discussed with recommendations for implementation based on the findings presented in this chapter.

5 Conclusions

This chapter concludes the thesis by summarising the key research findings in relation to the research aims and questions and discussing their value and contribution to the research community. The research questions are re-iterated, with a summary of key research findings, designed to address the key research questions raised in this thesis. Recommendations are given for implementation, including a practical application of the findings and specific recommendations for energy access policy makers and microgrid developers in Malawi. Application of the research and contributions towards the academic discourse in the field are then given, before highlighting limitations to the research, and opportunities for further research.

5.1 Summary of key findings in relation to feasibiliy and social impact of solar microgrids developed and operated as social enterpises

The overarching aim of this thesis has been to set out and test an argument for SMSE as a conduit for sustainably reducing energy poverty and achieving SDG7 in Sub-Saharan Africa, with the key objectives of proposing a methodology for assessing the feasibility of a SMSE, and testing it on a use case in Malawi.

This thesis has presented the concept of a Solar Microgrid Social Enterprise, proposed a set of general characteristics that define the social and enterprise aspects with respect to solar microgrids, and has outlined a specific approach for assessing the feasibility (ensuring appropriate implementation) and monitoring impact (building the evidence base). The proposed defining characteristics of a social enterprise include having a primary social purpose to provide electricity to all customers who want it, trade engagement in the marketplace, reinvestment of profit, community engagement and organisational accountability. The novel feasibility methodology includes pre-assessment, feasibility for a defined use-case, assessing market potential, and business modelling for scale up, while the impact evaluation methodology proposes a novel KPI framework to monitor and track performance and impact of solar microgrids. Each key research finding from this thesis is summarised below, addressing the research questions set out in the introduction of the thesis.

- *Are solar microgrids, deployed and operated as a social enterprise a feasible solution to provide sustainable, reliable and affordable energy at scale in low-income countries?*

The research has shown that solar microgrids have potential to be a feasible and cost-effective solution to provide energy in areas unlikely to receive the grid, and are increasing in prominence as energy access solutions in low-income countries. They have the potential to address multiple SDGs by enhancing socio-economic wellbeing through improved quality of life, access to public services, job creation and entrepreneurship opportunities and industrialisation enabled by access to energy. Their efficacy in achieving the challenge of SDG 7 specifically is largely dependent on the sustainability of the delivery model used to implement them. Private sector initiatives are showing promise to accelerate deployment of the nascent technology, but a purely profit driven approach is unlikely to deliver for the most vulnerable of society, ensuring no-one is left behind, as is the focus of the SDGs. Governments in developing countries best placed to invest in large infrastructure electrification programs, relying on development grants and loans, but are generally ill-equipped with the business innovation expertise required for effective and impactful solar microgrid delivery. Social enterprises, with social and environmental goals written into their constitutions, have greater potential for delivering solar microgrids with increased social impact and sustainability, offering a more robust mechanism that is better aligned to achieve SDG 7 in the Global South.

In Malawi, it has been found that solar microgrids are the most cost competitive solution for 37% of the population, with 42% of Malawians most cost effectively served by existing infrastructure, and 21% best served by standalone, or solar-home system. Additionally, solar microgrids have lower lifetime costs than diesel microgrids in all modelled locations in Malawi, although the addition of dispatchable diesel generation may provide benefits in larger, more urban systems. The quantified market potential for solar microgrids of approximately 6.5 million people is significant, and should be a key message for investment in the sector by donors and policy makers.

The figure of 37% is estimated to be the upper bound for the market potential, the actual market penetration of microgrid systems will depend on institutional support and favourable regulatory policies, recommendations for ways in which this could be accomplished are made in the following sections. Mapping the microgrid ecosystem in Malawi has revealed barriers to widespread implementation that include: an uncertain regulatory environment, low ability for end-users to pay, lack of access to finance, lack of local capacity for design and implementation of the technology, lack of mobile money integration, and limited local supply chain for consumer appliances as well as renewable energy equipment.

Based on results gained through piloting, solar microgrids have been found to offer reliable and sustainable energy, tracked through technical and economic Key Performance Indicators. Despite acknowledged challenges with smart meter connectivity, customers are able to receive a reliable electricity service and a SMSE can achieve financial sustainability operating at scale. Regarding affordability, cost reflective tariffs have been developed and trialled in a pilot site, with continued payments from the majority of customers indicating that solar microgrids can provide affordable electricity to communities in Malawi. However, for some poorer members of the community the service is too expensive, and in order to fulfil the social enterprise objective of connecting all customers that desire electricity while maintaining financial sustainability a suite of interventions is required outlined in proceeding sections.

- *Can SMSEs be financially sustainable in balancing ongoing costs of capital, operation and maintenance with income from electricity sales?*

The study has revealed that for the assumptions used and primary data harvested from the pilot microgrid, SMSEs are not financially sustainable currently, but have the potential to be with interventions of cost reductions and donor CAPEX. For a single microgrid, revenue covers site based operational costs, indicating a 100% donor funded CAPEX model would allow a SMSE to operate without additional financial support, while a portfolio of microgrids offers a positive investment case with a 50% CAPEX contribution from donor funding.

Based on primary pilot data, CAPEX costs for a single microgrid have found to be USD 8,869 per kW, or USD 1,700 per customer. Not included in these costs are development costs including staff time for site prospecting, community engagement, fieldwork, technical design and project management, as these were covered through donor funding which would increase the CAPEX costs of a single microgrid further, although would likely be shared between several sites in a portfolio. The costs are high compared to benchmarks in Africa and are largely attributed to the nascent microgrid market in Malawi, with costs expected to reduce as more pilot projects come online and economies of scale are achieved along with efficiencies in procurement and supply chains, and reducing costs of the components.

Site based operational costs for a single microgrid comprising site agent salaries, smart meter SaaS fees and data, and preventative maintenance contracts have found to be USD 3,797 annually. This does not include field and management staff costs, transport costs and business overheads, or depreciation, which again would be shared between multiple sites considered for a portfolio. Tariff bundles for different customer segments have been trialed based on Cost Reflective Tariffs calculated in the methodology. The Average Revenue per User (ARPU) for residential customers (USD 3.89) and business customers (USD 8.48) has been measured which offers insight on AWTP of rural customers, and informs financial planning of microgrid business models. The mean ARPU for 1 year of monitoring is 5.43 USD/month, which compares to a site based operational cost per customer of USD 5.27/month. This suggests a single microgrid site in Malawi can cover site based operational costs with a small contribution to CAPEX depreciation and wider business costs.

Considering an SMSE operating a portfolio of microgrids at scale, for the given assumptions, a 10 microgrid portfolio offers an unlevered IRR of 5.23%, and equity IRR of 4.43%, and an equity payback period of 17 years. The assumptions for this portfolio include a 20% reduction in OPEX and CAPEX as measured in the pilot projects and a 50% grant capital contribution from a donor. The inclusion of wider business costs which include community engagement considerations for a social enterprise have been incorporated. In summary, while the research shows that SMSE are financially sustainable operating at scale, the investment case can be improved through interventions in the Malawian microgrid ecosystem, discussed in more depth in section 5.2.

- *Do solar microgrids offer measurable positive social impact on the communities they serve including poverty reduction and economic development?*

A social impact focussed KPI framework has been developed and trialled to measure microgrid performance and impact of a microgrid pilot in Malawi. The value of remote monitoring and smart meter used in conjunction with customer survey has been demonstrated, as has the need for enhanced community engagement, fostering productive uses of energy, and developing innovative business models that balance income for operational costs and scale up with affordable tariffs.

Social impact data collected through surveys shows that energy access directly correlates with participants' expectations for happiness, opportunities, and economic development. Households are much more satisfied with their home lighting and can entertain, work and study in their homes at night. Energy supply infrastructure, availability, convenience, and environmental and health impact from microgrid energy has improved. Participants in the survey are generally satisfied with the quality of the service and the project; they consider it a good development, transforming life in the community and bringing an urban feel to it. However, some customers find tariffs expensive and unreliable, and did not always allow community members to pursue their business venture ideas.

Since installation, all microgrid customers have reported a reduction in use of non-microgrid devices including PSP, SHS, 12V Battery, and dry-cell batteries. This impacts many aspects of community life, including reducing environmental impact and pollution. Dry-cell battery reductions in particular will benefit the environment as batteries are rarely recycled and leak acid into the soil. As microgrid lighting became the primary lighting source for 100% of domestic customers, the use of solar home lighting and single charge torches decreased as expected.

40% of customers indicated access to health information has ‘very much improved’ or somewhat improved, but as a health centre has not been connected few other direct health impacts could be observed. The surveys suggests that children are spending more additional time studying in the home since installation, and the research shows that the material setting has changed, and now there are opportunities for learning practices to evolve. Electrifying schools and homes can change learning and study practices, enhancing the education children receive and their results in the long run. There has been an increase in total phone ownership, with an increasing proportion of smart phones. The microgrid offers in house phone charging for all customers indicators suggest contribution to social impact in terms of increased connectivity.

The number of businesses connected to the microgrid since installation has increased from 2 at the baseline survey to 14. Business incomes have increased, and customers feel less financially insecure since the microgrid installation. Although positive economic development is suggested, income and expenditure are challenging to accurately track, and subject to macroeconomic influencing factors.

In terms of female empowerment, 49% of all customers are women or girls and the data suggests positive impacts on female microgrid customers regarding perception of amount of free time, independence and decision making, respect within the community and household, and security in the home. The biggest changes are seen in respect within the community and household.

In terms of tariff and service, survey results have revealed and increase in satisfaction in Tariff price, payment method and value for money, however the electricity spend comparison, calculated as the average of current spend minus ideal monthly spend is over 40% of the monthly ARPU, suggesting the customers' ability and willingness to pay is still lower than the current tariffs.

Tracking social impact offers value in assessing the microgrids effect of achieving multiple SDGs, and offers a more nuanced and holistic view of the microgrid performance than just economic and technical metrics. Microgrid financial sustainability relies on satisfied customers that clearly benefit from the electricity offered through the microgrid, as well as a demonstration of the social impact experienced to investors and donors. The above 'impact signals' suggest that solar microgrids do hold potential to offer measurable positive social impact on the communities they serve including poverty reduction and economic development, acknowledging that potential externalities exist that could interfere with these signals and provide skewed perceptions or even misperceptions of the impacts.

5.2 Recommendations for implementation

Achieving a national microgrid sector in Malawi in line with Government and SE4All targets requires scale-up, replication and improvement of existing initiatives through a coordinated multi-stakeholder approach. Private sector (including social enterprise) led delivery offers the most promising approach to achieve the scale and speed required of the SE4All target of universal access to energy by 2030, however the Government of Malawi also has a critical role to play in enabling and accelerating deployment through clear and focused policy and regulatory frameworks. Furthermore, a step change in public sector funding from the Malawi government, donor partners and impact investment companies is necessary to accelerate solar microgrid implementation nationally. Accordingly, recommendations relating to the findings from Malawi are outlined below for microgrid practitioners and decision makers in policy, to accelerate access to energy through rapid deployment and scaling of solar microgrids based on the findings of this thesis.

5.2.1 Recommendations for policy makers and the regulatory ecosystem

5.2.1.1 Implement smart subsidies to reduce tariffs and improve microgrid financials

The market assessment outputs (Section 4.4) indicates that the cost of energy for microgrids in remote areas will be highest. Individuals living in these less accessible areas are also the least likely to benefit from grid-based electrification and are also the population least able to pay for their energy services. In order to provide financially viable services, the more remote populations will require some form of gap financing or subsidy scheme. Given that the accessibility of the location is the primary influencing factor to the Cost of Energy, a policy where higher system subsidies are offered in areas of greater remoteness, may be beneficial.

The high costs, low revenue and associated vulnerabilities in matching microgrid operational expenditure with income from electricity sales demonstrates the need for smart subsidies to enable solar microgrids to scale. As mentioned, subsidies for electricity supply in the Global North are ubiquitous, making it unfair and unsustainable to expect the most vulnerable communities to cover the entire cost of electrification without any assistance. The responsibility for serving the ultra-poor has traditionally fallen to the government or non-profits (charitable) sector, and has not been the responsibility of the private sector. SMSEs need to address the conflict of being financially viable while providing electricity to those unable to afford it, without compromising their sustainability. From a business viewpoint, microgrid developers are already struggling for unit economic viability and saddling them with additional costs will reduce their capacity to operate as a sustainable business, ultimately affecting their ability to serve customers who can afford them.

The use of smart subsidise can solve this, where the government pays microgrid developers to connect and offer a reliable electricity service to rural customers. The challenge lies in identifying low income households and how to direct subsidies in a way that does not distort markets but offers support to balance affordable tariffs with sufficient resources to operate the microgrid sustainably, while allowing a surplus to be built up to replace components at end of life. Through sharing of data on costs and income between multiple active microgrid projects, a case can be made to government based on a quantification of the subsidy required and this economic modelling should be the subject of economic modelling and research.

5.2.1.2 Operationalise microgrid regulations and integrate microgrids into rural electrification planning

Ecosystem mapping outputs (Section 4.4.6) indicate regulatory progress is being made with the recent mini-grids framework and national energy policy, but work is still needed in putting policy into practice. Whilst policies relating to quality standards of PV equipment are in place, various agencies need to do more to ensure enforcement and promote product quality standards and raise consumer awareness. Despite a draft rural electrification plan in place, uncertainty exists regarding future plans for grid expansion, putting microgrid developers at risk of grid encroachment leading to stranded assets. This threat can be alleviated through defining geographic areas or zones that are demarcated for microgrid development, de-risking the sector and attracting more investment. Additional confidence can be gained through clear understanding of what happens when the grid does arrive, with procedures set in place for microgrid to grid interconnection. Central grid operators gain from additional generation and distribution grid infrastructure that have already been paid for, while further risk reduction is offered to microgrid operators.

5.2.1.3 Invest in research and capacity building

Microgrid ecosystem analysis (Section 4.4.5) and assessment of pilot experiences (section 4.6) has shown that capacity development within the solar microgrid sector is required to make the technology scale, at all levels ranging from project development, site selection, project management and finance as well as local capacity building for operation and maintenance. Business and finance training for microgrid developers and a greater focus on learning from international best practice will also lower barriers to entry and foster a thriving Malawian microgrid sector. These efforts should be maintained and iteratively improved upon in order to fill any capacity caps still present, collaboration between the private sector, government and educational institutions will be important to effectively deliver these capacity building projects.

There is a lack of skilled technicians, system designers and business expertise in the Malawian microgrid sector and efforts are required to address this through targeted capacity building. This can include government support for technical short courses, degrees offered through local universities, online training and internship opportunities both local and international. The government can also support private sector capacity building through business development initiatives such as tailor-made technical assistance, business incubation and acceleration programs. Capacity building can also be supported for private sector operators on access to finance through bank loans and also business planning/management skills. The government can also accelerate microgrid deployment by investing more in microgrid research and development in partnership with the academia, for example through directly providing research funding or innovation challenges, in line with the research agenda proposed below. Further engagement with Malawian educational institutions is necessary to understand the content and focus of existing courses, with specific consideration of the capacity gaps identified through collaboration with private sector, third sector and government actors. Through this technical capacity assessment, recommendations to systemically improve education practices and resources for the off-grid energy sector in Malawi may be made.

5.2.2 For microgrid developers, both development partners and private sector

5.2.2.1 Improve financial sustainability through innovative business modelling

Business modelling analysis (Section 4.5) has shown that a key challenge currently preventing microgrids from scaling in Malawi is proven business models with positive cash flows, one that can be addressed through learning from other successful initiatives in SSA [14] [319] [320]focus on sustainability can be fostered through ensuring a long-term project vision with development of sustainable business models with funding being sourced from local and national sources as well as external donors. Learning from existing innovative projects in Malawi can be utilised to inform the nascent microgrid sector in Malawi through roundtables and working groups.

In order to practically address challenges in achieving financial sustainability, practitioners have two options: reducing costs or increase demand. Suggestions for cost reductions for CAPEX include bulk purchasing to achieve economies of scale and for OPEX, ongoing business modelling when operating multiple microgrid sites should prioritise efficiency in maintenance operations and fieldwork activities to minimise transport and labour costs. Consumers face affordability challenges, and microgrid developers need to innovate in pricing and payment methods. PAYG tariff and mobile money offer another innovation that can reduce costs, increase accountability and efficiency in payment collections. Adopting consumer financing business models for provision of appliances to customers will further foster uptake in electricity use and associated revenues for the microgrid operator.

As one of the world's least developed countries, the uncertainty surrounding the ability of end users to contribute to the financial cost of any electrification system is a barrier to scalable implementation. To mitigate this barrier, embedded PUE should be prioritised as a key customer base to enable income generation and subsequent increased ability to pay amongst end-users. Additionally, the initial choice of sites for any microgrid should prioritise sites with existing market centres, and high energy use, in order to make use of existing economic activity and benefit from the lower cost of energy associated with larger capacity systems.

5.2.2.2 Conduct further pilots through collaboration with multiple development players

Further pilot projects are needed to better understand local costs including import duties, along with transport costs and other costs incurred by a long supply chain to be accurately model project financials. Additionally, the extent of the cost benefits associated with economies of scale need to be further investigated to avoid consideration of the Malawian microgrid sector as a static entity. Efficient technical design and sustainable business models are improved with access to and analysis of primary data from existing microgrids. Monitoring Key Performance Indicators from further pilots in technical, economic and social impact domains, and sharing this data will aid in building the knowledgebase and accelerating the nascent microgrid sector.

To achieve this, and for sustainable and accelerated microgrid deployment more generally, collaboration is necessary across all initiatives, between social enterprises, community members, local NGOs, the local government, and agencies working on the project. Coordination and consolidation of donor led initiatives in the microgrid sector is needed to avoid duplication; microgrid developers should network with all levels of energy-related organisations, such as NGOs, the government, the commercial sector, and research institutes.

5.2.2.3 Invest in technological innovation

Technical innovations for solar microgrids including smart metering, data logging, remote monitoring and control have been shown (Section 4.6) to offer efficient, technically robust and sustainable systems resulting in reliable electricity provision for their customers, and should be embraced by microgrid developers. Efforts should be made to explore supply chain option for such technology, as well as developing opportunities for local manufacture to increase the local value chain elements, spurring economic development. The value of remote monitoring has been demonstrated in terms of reducing maintenance costs and providing better understanding of system performance, as well as a tool for troubleshooting and providing early warnings when issues are about to occur. As microgrid operators transition to operating a fleet of microgrids, the need for remote monitoring in parallel with robust asset management strategies becomes obvious, and should be a focus of investment in hardware and human capacity from the outset.

Similarly, the value of smart meters is clear, as it offers remote access to customer data, remote switching and dynamic tariff changing. The technical challenges experienced with the smart meters through this project are deemed to outweigh the benefits in terms of data and control, and in the long run are seen as an essential element of any solar microgrid system. A specific consideration of the identified barriers to PAYGo business models and mobile money in Malawi should be examined, with reference made to the ways in which these have gained mainstream use in other countries in East Africa where initial barriers may be comparable.

Utilising such technologies will also promote transparency and accountability in microgrid business strategies. Practical barriers such as high transaction fees and up-front costs associated with the inclusion of such technology can be addressed through collective action from the Malawi energy industry to lobby for reduced transaction fees. Alternatively, if opting for mobile payments, microgrid developers could consider payments to suppliers from the mobile money account, to avoid transaction fees entirely.

5.2.2.4 Understand the importance of measuring impact

The benefits of social impact measurement have been demonstrated (Section 4.6.5), and should be conducted to inform business strategy, while also shared with government to make better informed decisions on resource allocation and to have better understanding of solar microgrid services. Noting the above observations of social impact offered through the microgrid, it is highlighted that the project has just provided electricity, and has not conducted in depth community engagement towards enhancing social impact. Microgrid projects for rural electrification on their own are insufficient to significantly combat poverty alleviation through stimulating production practices or increase households' income, but they can be the means to that end. The microgrid technology indeed can contribute towards improvement in health, education, and gender-related issues but additional community engagement is required to enhance the effects, such as PUE training, appliance financing, and gender focused engagement. The socio-economic effect is a complex topic without a straightforward recipe for success. In order to effectively combat poverty, microgrid projects must cover a variety of topics and the involvement of multiple stakeholders should be sought to guarantee a successful transdisciplinary approach and lasting results. For any positive social change to occur, trust must be built in the community through clear accountability, with frequent community engagement encouraging bi-lateral communication. Similarly, in order to promote socio-cultural understanding and a better comprehension of social impact, a collaborative community should be created in which projects can be informed by already existing projects, and can exchange or lend expertise and specialists, including local social scientists.

5.2.2.5 Acknowledge the value of and set aside resources for community engagement

For poor, dispersed rural communities, electricity supply is often not enough. Sustainable microgrid projects must be designed to be run as businesses with livelihood components to increase community income built in, rather than assumed to evolve from the provision of electricity. To achieve this, microgrid developers need to better appreciate and integrate the needs and capacity gaps of rural communities and be able to serve them in an efficient and impactful way. Local capacity building and community engagement thus needs to be prioritised for effective microgrid enterprises to function and grow sustainably, with a budget allocated to support these interventions. Community engagement should be a key focus embedded in the service offering of a microgrid developer, with financial and human resources set aside in the business plan to cater for these social requirements, enabling better service, happier customers, higher demand and net positive balance sheets.

5.3 Summary of novel contributions

The research provides contributions to the field of energy access planning, specifically in relation to feasibility planning for solar microgrids operating as social enterprises, including definitions and literature explorations, financial assessment for single and multiple sites, market quantification and geospatial planning, and social impact quantification through KPIs. Specific contributions to the relevant academic discourse are listed below:

- Literature based exploration of solar microgrids and social enterprises, proposing a set of defining characteristics of a Solar Microgrid Social Enterprise
- Development of a methodology to assess the feasibility of a SMSE, comprising assessing financial sustainability and tracking social impact. The methodology uses established methods, combining them within a novel framework for proposed use in low-income countries in Sub-Saharan Africa.
- Conducting a site-specific feasibility study through comparison of cost reflective tariffs and customer ability and willingness to pay,
- Proposal and development of a novel method for assessing the market potential for solar microgrids though quantifying the market through linking techno-economic modelling to GIS mapping
- Using single site feasibility and market assessment outputs to model financial sustainability of an SMSE operating a portfolio of microgrids at scale, utilising new industry tool Odyssey.
- Development of a novel Key Performance Indicator Framework to monitor performance and impact of solar microgrids, specifically designed to better understand the social impact offered by solar microgrids to the communities they serve.

These contributions add to the discourse on energy planning, both in spatial assessment comparisons of least cost electrification pathways and financial feasibility assessment. The market assessment methodology application adds to previous studies in Ethiopia [216] , and offers data points and recommendations to be compared with other studies using tools such as OnSSET [222], it employs a novel use of HOMERPro and aiding decision makers in energy access. The literature review revealed a gap in quantitative research testing social enterprise business models, and this research provides an evidence base to progress academic discourse on social enterprise in energy access.

The methodology has been utilised on a case study in Malawi, providing analysis of primary data from in a nascent market with little to no previous published data. Specific contributions to the energy access and microgrid sector in Malawi are summarised below:

- A quantification of the market potential for solar microgrids in Malawi, based on cost competitiveness against grid expansion, diesel generators and solar home systems.
- Mapping of the Malawian microgrid ecosystem, revealing opportunities and barriers supporting or preventing microgrids from scaling in Malawi, with targeted recommendations provided to policy makers and microgrid developers to overcome the barriers.
- Primary data on CAPEX and OPEX for a microgrid installed in Malawi, using 12 months of operating data.
- Demand data for previously unconnected microgrid customers, including load profiles for residential, business, and institutional customers.
- Indicators of Ability to Pay of rural Microgrid customers have been presented, through measured revenue collection from a pilot microgrid.
- The utilisation of the KPI indicator framework in Malawi has revealed key insight on solar microgrid performance and impact in Malawi measured in technical, economic and social impact themes.
- An evidence base has been presented for use as advocacy toward subsidies for microgrids in Malawi.

The market quantification of solar microgrids itself offers a clear message for investment in the sector, while the specifics of Cost of Energy and market locations aids energy planners such as the Ministry of Energy in their important work to design and implement national least cost electrification pathways. The findings complement existing studies such as the Malawi Integrated Energy Planning tool and can inform future iterations of policy frameworks such as the Malawi Minigrids Framework or National Energy Policy.

The quantification of single site and portfolio SMSE financial sustainability and investment case is a first in published literature for Malawi. The findings offer an initial indication that an investment case, while currently modest, does exists, and signposts potential pathways to improve the case towards a national microgrid programme.

Following on from the above, the collection, monitoring and analysis of primary data offers significant utility to the nascent microgrid sector in Malawi, where no previous published studies sharing primary data of solar microgrids could be found. Application of the findings relating to customer demand, ability to pay and CAPEX and OPEX costs are of significant value to investors, policy makers and microgrid developers to inform technical design and business models. Additionally, academic researchers will find value in the data not only in Malawi but also studies comparing regional feasibility, performance, and impact of solar microgrids.

5.4 Limitations

A significant limitation in terms of primary data is the sample size, with data only available from one microgrid to inform the majority of the analysis. Several subsequent modelling assumptions are used from this primary data, offering potential inaccuracy. The availability of primary data is limited by the scope of the EASE project and the nascent state of Malawi's microgrid sector. Although valuable as the only published microgrid primary data for Malawi, further piloting data would offer value in fine-tuning the results. The study would be further improved but replicating the methodological steps, but this was not possible due to time challenges.

5.4.1 Feasibility study for a defined use case

- The use of expressed WTP is recognised as offering high uncertainty. Survey questions are subject to 'gaming' by potential microgrid customers, with answers normally higher than genuine affordability once electricity arrives. In nascent markets data is sparse, and these data points still provide utility. As further microgrids are piloted, smart meter analysis will reveal paid Average Revenue Per User for different customer segments and the WTP surveys will no longer be necessary.

5.4.2 Market assessment

- A number of assumptions were made in the process of this techno-economic assessment and mapping process, the key limiting assumptions are detailed in Appendix 7.12. Due to project implementation constraints, the Market Assessment was conducted chronologically first, and does not utilise pilot data. Further iterations with new up to date datasets can address this and increase accuracy of market assessment outputs.
- The assessment is static and considers variables only as they existed at the time of modelling, or as recently as data was available and makes no explicit attempt to anticipate trends or how the market for microgrids will evolve.
- It is possible that the proportion of the population assumed to be best served by grid electrification is an overestimation, as a significant number of people live within the grid and lights exclusion zone who may not have access to existing infrastructure due to prohibitively high connection costs. The Malawian grid also experiences regular blackouts, so even populations living close to the grid or with existing grid connection may benefit from under the grid, or grid-parallel

microgrid installations. On balance, however, it is possible that larger communities within the microgrid inclusion zones are candidates for grid connection, that remains un-reflected in the grid data used in this assessment, and so a small number of relatively large population centres may be incorrectly considered as microgrid candidates rather than grid extension candidates.

5.4.3 Business modelling for scale

- Utilising measured load profiles from one microgrid to predict demand at another site offers novelty and a valid first step for analysis but also introduces uncertainty. Similarly the use of measured 8760 load data offers valuable primary data to inform analysis, however more granular load profiles for different businesses types will increase accuracy. Increased accuracy could be gained through more detailed energy use surveys at each site for comparison, consolidation of further microgrid pilot data, and further analysis comparing the two. The load profile is the most crucial aspect and has the greatest influence on finances, thus decreasing the unpredictability of load profiles is essential. This limitation correlated with budget and resource constraints within the pilot project programme.
- Similarly, replicating identical tariffs across all portfolio sites misses opportunities for bespoke tariffs for specific businesses or energy users. A counter argument to this would pose that setting different tariffs at different sites will create tensions between communities and as a social enterprise a measure of equality must be observed. As more pilot data emerges more detailed business planning can be conducted to investigate unique tariffs for specific business customers, but this modelling is deemed out of scope for this thesis.
- The assumption of AWTP applicability from one site to another in the same district is justified but is also highlighted here as a source of uncertainty, as each microgrid site is unique in terms of local economic activity and appetite for microgrid electricity. Such assumptions can be tested through further pilot data.
- In the final financial scenario modelling the cost assumptions for CAPEX and OPEX are reduced arbitrarily at 20%, based on perceived realistic potential for cost reductions. Further investigation into portfolio operational efficiency savings and bulk purchasing economies of scale will reveal more accurate CAPEX and OPEX at scale inputs. This research is challenging due to the limited number of microgrid pilots available to study and opportunities to pursue such avenues will become possible as more pilots emerge.

5.4.4 Piloting and KPI framework

- Further KPIs in technical, economic and social impact could have been developed to explore different elements of microgrid performance and impact investigation. Several additional KPIs were considered but omitted to keep the scale and scope of the research within reasonable boundaries.

- Social impact data analysis is restricted by project and data collection time constraints, with a short time frame for observing impacts from microgrid interventions. Longitudinal studies offer more nuanced and informative results, but were out with the available data collection potential of the EASE project.

5.5 Chapter summary

This chapter has provided a summary of the key thesis findings in relation to the research questions posed in Chapter 1. It has highlighted the thesis contributions, provided recommendations for policy makers and microgrid practitioners, and listed limitations to the methodology presented. Future research areas have been highlighted. A methodology for assessing the feasibility of SMSE has been shown to be valid with areas highlighted for improvement, while within the specific use case of Malawi, SMSEs are shown to be financially feasible on a portfolio level with capex grant funding contributions, and significant potential to offer social impact to communities served. Chapter 6 concludes the thesis by proposing future research.

6 Future Research

The evidence presented in this thesis shows that SMSEs are a plausible way to provide electricity access for millions and provide a practical, bottom up pathway to high tier electricity access. In order to fully realise the potential of SMSE, a range of further work is required which this chapter proposes.

6.1 Repeat the methodology

The methodology for assessing the feasibility of a SMSE has been tested in Malawi for the first stage of a scaled SMSE, namely operating a portfolio of 10 sites. Further validation of the methodology and utility will be gained through repeating the methodology: firstly, again in Malawi for a SMSE operating at different stages of development (larger portfolio sizes), and secondly in different low-income country nascent microgrid markets. For the former, the validity of using the methodology with data from multiple microgrids, and modelling a national/regional level deployment (as the methodology was originally intended for) would offer significant value to Malawi's microgrid sector. The methodology has been designed for iterative use and as more pilot data emerges the accuracy for the outputs increases. For the latter, conducting an ecosystem mapping exercise in different country contexts would provide a wealth of information regarding similarities and differences, and lessons learned in overcoming barriers to microgrid deployment that can be shared to accelerate deployment.

6.2 Techno-economic business modelling

More research is required to develop and trial microgrid business models, linked with innovative financing mechanisms. As the microgrid sector transitions from single pilot projects like those presented in this thesis to scaled operations the funding must similarly change from donor funding to income from tariff sales and subsidies. Designing the most effective tariffs for different customer segments and quantifying smart subsidies needed for microgrids to be financially sustainable while offering the social impact desired by governments is a valuable and necessary research agenda to accelerate microgrid deployment. Additionally, PAYG business models should be more specifically assessed in order to understand the barriers and draw out recommendations to facilitating PAYG and/or mobile money integration into microgrids in Malawi. Acquisition and analysis of further primary technical, economic and social impact data from microgrid pilots will be essential in informing this research.

6.3 Measuring and understanding microgrid demand

The study has demonstrated the utility in understanding demand of newly electrified microgrid customers, and highlighted the paucity of demand data in Malawi. Measurement of load profiles through further pilot projects, quantification of load growth over time and providing insight on demand patterns and seasonal trends is essential for designing cost effective and technically efficient microgrids and should form a central theme to future microgrid research in Malawi. Measuring and sharing demand disaggregated by customer segments is especially important for informing business models and tariff setting, and further research can compare energy use surveys to measured load profiles, allowing for more accurate demand prediction.

6.4 Asset management of microgrid portfolios

Assuming the microgrid market grows and future microgrid operators will own and manage multiple microgrid sites, valuable research is needed to inform asset management strategies to sustainably manage a fleet of microgrids. Such research will predict timings for replacement components, optimise maintenance regimes, and maximise cost savings and technical efficiency through remote monitoring. Such modelling of portfolio scale operations will provide more accurate OPEX costs to feed into the methodology.

6.5 Productive uses of microgrid energy

Stimulating daytime demand has been shown to be a key enabler of increasing utilisation and revenues for SMSEs. Identifying anchor loads in rural areas that can be powered by solar microgrids, and integrating the PUE appliance to microgrid systems will be a game changer for microgrid business models and investment cases. A multi-disciplinary approach is required, as in addition to technical integration of PUE appliances to match generation capabilities, business design of the PUE enterprise is needed, including exploration of value chain analysis, appliance financing and key maker models. As the majority of rural incomes in Malawi are derived from farming, anchor loads offering agricultural processing are likely to be most viable and should be considered as a priority.

6.6 Exploring linkages and trade-offs with SHS and microgrids

The Levelised cost of energy for Solar Home Systems should be found and compared with the microgrid cost of energy for rural, dispersed, low population areas to verify the assumption that micro-grids are best suited for electricity provision in these locations. Stakeholder judgement may be necessary in considering the ‘value’ trade-off between a potentially slightly higher cost of energy and the capacity for productive uses. Very sparse rural populations will likely remain unviable for grid or microgrid connection for the foreseeable future, leaving approximately 3.7 million people (21% of the population) without access to electricity or with SHS as their most practical option, constraining their opportunities for economic development. The potential for scalable or interconnected SHS may expedite the improvement of this demographics’ access to electricity in the medium to long term [321] and should be investigated. Further innovate research should explore interconnection of SHS with microgrids or DC mesh networks.

6.7 Grid integration and interconnecting microgrids

As the grid expands to rural areas an inevitable consequence will be a convergence with existing microgrids, offering both a threat (of stranded assets) and an opportunity (to sell excess power) to microgrid developers. Research on technical, business and regulatory arrangements for interconnecting the national grid with microgrid is much needed as has yet to be trialled in Malawi. Similarly, as more microgrid are installed, the opportunities for interconnecting microgrids offer shared generation and storage, improved efficiencies and innovative business models which can lower tariffs and increase resilience. Thus, research on grid integration and interconnection of microgrids in terms of technical and business planning should be on research agendas.

6.8 Social impact

Longitudinal studies of the impact of electricity with cross-disciplinary collaboration between social scientists, engineers, anthropologists and economist among others will inform the effectiveness and impact the microgrid has on the community it serves and shape recommendations for additional interventions to be implemented alongside providing a secure electricity connection. A general recommendation is given for more social impact surveys to be conducted by microgrid practitioners to understand the impact the microgrid has on the community it serves. Frameworks and best practice guides, including those proposed in this thesis can be followed and adapted to include more KPIs to reveal a more nuanced understanding of impact.

6.9 Market assessment

The techno-economic modelling and mapping methodology steps demonstrated in the market assessment could also be used for scenario planning for policy levers such as different levels of subsidy for micro-grid components, diesel price shocks (or fuel shortages), population growth, increased accessibility (or inaccessibility), post-installation demand-growth, climate change and the impacts of grid-expansion. Given both diesel generation cost and maintenance trip costs are modelled as being dependent on diesel fuel pump price, sensitivity analyses should be conducted to consider the likely future costs of diesel fuel, and how shocks such as fuel shortages would affect the cost of energy, and the benefit of solar-diesel hybridisation where preliminarily recommended. Furthermore, including additional renewable technologies in the market assessment comprising hydro, wind, and biomass gasification would add value to the study.

7 Appendices

7.1 Odyssey outputs and calculations

Acronym	Definition	Calculation
EBITDA	Earning Before Interest, Tax and Depreciation	Total Revenue - Total Operating Cost - Overhead Cost
EBIT	Earning Before Interest and Tax	EBITDA - Depreciation and Amortization
EBT	Earning Before Tax	EBIT – Tax
NP	Net Profit	EBT – Tax
NPV	Net Present Value	= - FCF0 + NPV(FCF1, FCF2, … , FCFn)
FCF	Operational Cash Flow - Investment or Re-investment	
IRR	Internal Rate of Return	'= IRR(FCF0, FCF1, FCF2, …, FCFn))
DCSR	Debt service coverage ratio	
LCOE	Levelized Cost of Electricity (The *NPV of the unit-cost of electricity over the lifetime of a generating asset*)	
WACC	Weighted Average Cost of Capital	
n/a	Payback Period	The length of time required for an investment to recover its initial outlay in terms of profits or savings. It is indicated by the first positive cumulative FCF.
n/a	Depreciation	(Upfront cost for depreciation/ Depreciation Duration) + (Replacement cost (*if applicable)/Depreciation Duration)

7.2 Social Impact questions

Table 51 Demographic Survey Questions

Question Type	**Question**	**Choices**
text	Name of Participant	
text	participant phone number/customer number	
Select one	Gender of Respondent	Male, Female
Select one	Are you the head of the household?	Yes, No
Select one	What is the highest level of education you have reached?	Relevant local education levels 9 e.g. primary, secondary, tertiary)
integer	How many people are in the household?	
integer	Aged 0-6 (male/female)?	
integer	Aged 7-17 (male/female)?	
integer	Aged 18 and over (male/female)?	
Select one	What are your wall made of?	Burnt brick with cement, Mud Bricks, Metal Sheets, Wood, Cement Blocks, Mud, other (specify)
Select one	What is your roof made of?	Corrugated iron sheets, Tiles, Metal sheets, Grass, Plastic sheets, other (please specify)
Select one	Have any alterations been made to your house in the last 6 months, excluding the microgrid wiring? Please give details	Yes, No

Table 52: Access to electricity questions

Question type	Question	Choices
Access to electricity		
Select multiple	Which of the following does your household use?	PSP, SHS, 12V battery, Generator, Single use batteries, none
integer	For each selected: How many does your household own that are functional?	
Select multiple	For each selected: What is it used to power?	List of lighting/appliance applications
Select one	Generator selected: how often do you purchase fuel?	5 stage likert scale
integer	Generator selected: how much fuel do you usually purchase?	
integer	Generator selected: how much does this amount of fuel cost?	
Select one	Single use batteries selected: how often do you purchase batteries?	5 stage likert scale
integer	Single use batteries selected: how many batteries do you usually purchase?	
integer	Single use batteries selected: how much does this amount of batteries cost?	
Select multiple	Single use batteries selected: What devices does your household use single use batteries to power?	List of lighting/appliance applications
integer	12V Battery selected: How many 12V batteries does your household own that are functional?	
Select one	12V Battery selected: how often do you charge these batteries?	5 stage likert scale
integer	12V Battery selected: How much does it cost to charge these batteries?	
Select one	Does the household have access to electricity from any other sources not already mentioned? (e.g. micro-hydro, wind turbine, biogas generator), please give details	Yes, No
Select one	Overall, on a scale of 1 - 5, how happy are you with your household's current level of access to energy?	5 stage likert scale
Lighting		
Select multiple	Which of the following lighting devices does your household use?	kerosene or paraffin lamps, torches (single use batteries/ rechargeable/phone, candles, generator powered lights, SHS
Select one	Overall, which is the household's main lighting device?	
Select one	Overall, which is the household's secondary lighting device?	
integer	For each selected: How many devices does your household own?	number of lamps owned
Select one	For each selected: how often do you purchase fuel/replacement?	5 stage likert scale
Text	For each selected: how much fuel/replacement do you usually purchase?	
integer	For each selected: how much does this amount cost?	
Select one/text	Does the household own and regularly use any other sources of lighting? Please give details	
Select one	Overall, on a scale of 1 - 5, how happy are you with your current lighting devices?	5 stage likert scale
Appliances		
Select multiple	Which of the following appliances do you own?	Radio stereo computer TV fridge, phone, other
integer	How many *appliance* does your household own? (repeat for radio, stereo, computers, TV, fridge,	
Select multiple	Who in the household uses a *appliance*?	List of household members
integer	How many *appliance* does your household own?	
Select one	Overall, on a scale of 1 - 5, how happy are you with your current level of access electrical devices?	5 stage likert scale

Table 53: Health, Education and Communication survey questions

Question type	Question	Choices
	Education	
integer	How many school aged children in your household do not go to school?	
integer	How many children do school work in the home?	
integer	How many hours do children do school work in the home per WEEK?	
Select one	Do children from other households come to do school work in your home?	Yes, No
Select one	Do any adults in the household attend night time education?	Yes, No
	Health	
Select multiple	What is your main source of accessing health information?	TV, radio, news, smart phone, health facility, social gatherings, other
Select one	Has your access to health information changed in the last 6 months?	5 stage likert scale
Text	How so?	
Select one	Has your family's health changed in any way since accessing the microgrid?	5 stage likert scale
Text	Please give details	
	Communication	
Select one	How often do you access local news?	5 stage likert scale
Select multiple	How do you keep up with local news?	Conversation, Social gatherings, Community groups, Radio, Newspaper, TV, Mobile phone, other
Select multiple	How do you keep up with national news?	
Select one	How often do you access local/national news?	5 stage likert scale
integer	How many mobile phones does your household own?	
integer	How many of these would you consider to be smart-phones? (access to internet, news, social media)	
Select multiple	Who in the household uses a phone?	List of family members
Select one	Who in the household uses a phone most often?	
Select multiple	What do people in the household use the phone for?	talking (Friends and family), talking (Business), SMS/sending texts, Games, Social Media, News, Internet, Other
Select one	Overall, on a scale of 1 - 5, how happy are you with your current level of access to mobile phones and their performance?	5 stage likert scale

Table 54 Employment and finance questions

Questions type	Question	Choices
	Household Income	
integer	What is the average, highest and lowest amount the household typically earns in a MONTH?	.
Select one/text	Has your income changed in the last 6 months? Why?	Yes, No
integer	What is the average, highest and lowest total expenditure the household typically earns in a MONTH? includes food, household items, airtime, remittances, energy, rent, education, health, clothes and other expenses	
Select one /text	Have your expenditures changed in the last 6 months? Why?	Yes, No
Select one	Overall, on a scale of 1 - 5, how secure do you feel your household's finances are?	5 stage likert scale
Select one	Are you, or a member of your household, a member of a village savings and loans group?	Yes, No

text	How much do you/they give per MONTH?	Yes, No
Select one	Do you, or a member of your household, have a bank account?	Yes, No
Select one	Does your household have access to credit?	Yes, No
Select one	Has your household taken credit in the last 6 months?	Yes, No
integer	How much was borrowed (in the last 6 months)?	
Select one	Does anyone in the household have a mobile money account?	Yes, No
Select multiple	Has its usage changed in the last 6 months?	5 stage likert scale
	occupation/employment	
Select one	Have the occupations of anyone in household changed in the last 6 months? e.g. new work/job losses/started new business/seasonal work started or ended	
Select one	What was their occupation before?	List of typical jobs
Select one	What is their occupation now?	
Select one	Is the occupation better or worse than before?	5 stage likert scale
Select one	Has the amount they contribute to household finances increased or decreased?	
Select one	On a scale of 1 - 5, how happy are you with your employment situation?	
Select one	Do you own or run a business from this property?	Yes, No
Select one	What type of business is it?	List of typical businesses
integer	How many paid/waged employees are there?	
integer	What is the business' average, maximum, and minimum monthly income?	
integer	What is the business' average, maximum and minimum monthly expenditure?	
Select one	Are you or anyone in your household using the microgrid electricity connection for income generating activities?	Yes, No
Select one	Has the household generated additional income as a result of the micro-grid?	Yes, No
integer	Could you estimate how much additional income per month?	
Select one	Has the household had any additional expenditure since the installation of the micro-grid?	Yes, No
integer	Could you estimate how much additional expenditure?	
Select one	In your opinion, have any new job opportunities been created in the community since the installation of the micro-grid?	Yes, No

Table 55 Female Empowerment survey questions

Question Type	**Question**	**Choices**
Select one	Is the respondent female? (next questions only if yes)	Yes, No
Note	For you personally, what effect has having an electricity connection had on the following:	
Select one	Amount of free time	5 scale likert: very much increased, somewhat increased, remained similar, somewhat decreased, very much decreased
Select one	recreational activities	
Select one	household responsibilities	
Select one	level of tiredness	
Select one	Independence and decision-making power	
Select one	Respect within the household	
Select one	Respect within the community	
Select one	Security in the home	
Select one	In your opinion, has the microgrid had an impact on female members of your household specifically?	Yes, no
Text	Please give details	
Select one	Who makes decisions about purchasing appliances in the household?	

Select one	Whose decision was it to become connected to the grid?	Myself, Spouse, Mother, Father, Brother, Sister, Son, Daughter, Other
Select one	Are evening activities usually different for males and females in the household?	Yes, No
Select multiple	How do male members of the household usually spend their evenings?	Working, cooking, other housework, caring, social, free time, other (please specify)
Select one	Which of those activities do male members do the most in the evenings?	
Select multiple	How do female members of the household usually spend their evenings?	
Select one	Which of those activities do female members do the most in the evenings?	

Table 56: Tariff and Service survey questions

Question type	**Question**	**Choices**
Tariff		
Select one	What tariff are you currently on?	List of tariffs
Select one	Have you changed tariffs since first getting a connection?	Yes, no
Select one	Why did you change tariffs?	It was too expensive, I wanted to use more electricity, Other
Select one	On a scale of 1-5, how happy are you with the method of paying for your tariff?	5 scale likert
Select one	On a scale of 1-5, how happy are you with how much you pay for your tariff?	5 scale likert
Select one	Do you feel the service offered is value for money?	5 scale likert
Select one	Are the payments for electricity a burden?	5 scale likert
Select one	Do you cut back on your use because you can't afford the service?	5 scale likert
integer	How much are you currently spending per month on microgrid electricity?	
integer	How much would you ideally be paying per month on microgrid electricity?	
Select one	Does your household spend more or less on energy per MONTH since the microgrid was installed? Could you estimate how much?	5 scale likert
Microgrid service		
Select one	To what extent has the quality of life of you and your household changed since getting the connection?	5 scale likert
Select one	On a scale of 1 - 5, how likely would you be to recommend the minigrid to a friend?	5 scale likert
Select one	How does the system compare with your expectations?	5 scale likert
Select one	Have you experienced any technical problems with your connection?	Yes, No
Select one	Have these been resolved satisfactorily?	Yes, No
Select one/text	Are there any negative consequences of being connected to the micro-grid? please give details	
Select one	Do you feel safer in your homes as a result of the microgrid connection?	5 scale likert

7.3 Key Performance Indicator list

Table 57: Suggested list of Key Performance Indicators, indicators used in the case study highlighted

INDICATOR	UNITS	Data Collection[4]
TECHNICAL INDICATORS		
Daily communication uptime	days	SM
Number and length of planned/unplanned power outages	#, days	SM
Number of unplanned power outages	#	RM
Length of power outage	hh:mm	RM
Amount of fuel used	litres	PD
Monthly/annual electricity production	kWh/month or year	RM
Battery state-of-charge - daily, weekly, monthly	VDC	RM
Current in and out—for system performance information	A	RM
Battery efficiency—for system efficiency information	%	RM
Battery temperature—to monitor battery health	°C	RM
Utilisation rate	%	SM
Voltage imbalance	%	RM
Transients	#	RM
Voltage variations	#/day	RM
Frequency variations	avg deviation in Hz/time	RM
Average power	kW	RM
Maximum power	kW	RM
Average number of hours in a day that power is available	hours/day	RM
Time of power availability	time	RM
Availability of power (Both daily and seasonal)	Average hours of availability per day, year	RM
System Average Interruption Frequency Index (planned and unplanned)	Total number of customer interruptions/total number of customers	RM
System Average Interruption Duration Index (planned and unplanned)	Total minutes of customer interruptions/total number of customers	RM
Renewable energy penetration	(renewable kWh/total kWh) %	RM
Annual electricity production	kWh	RM
Duration of daily service	hours/day	RM
Customer segment monthly total and average consumption	kWh per month, load profiles	SM
Household aggregate demand	Total peak/average load drawn by households	SM
Businesses and industry aggregate demand	Total peak/average load drawn by businesses and industries	SM
Institutions aggregate demand	Total peak/average load drawn by community services	SM
ECONOMIC INDICATORS		
Monthly payment collection rates (number of payments/number of customers) or customers behind on payments	%	SM
Total energy sales revenue	USD/month	SM
Other revenues (e.g., from other services offered, monthly service charges, or connection fees)	USD/month8	PD
Average monthly revenue per user	USD/month	SM
Customer segment revenue	USD/month	SM
Cost per connection	USD/connection	PD
Cost per kW installed	USD/kW	PD
Total cost of power	USD/kWh	PD
Total losses (kWh generated/kWh sold)	%	RM,SM
Number of new connections per month	#/month	PD
Number of disconnections per month	#/month	PD

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[4] **RM = Remote Monitoring, PD = Project Documentation, SM = smart Meter, S = Surveys**

SOCIAL INDICATORS		
Demographics		
Number of people in household, gender disaggregated	#,	S
Community services connected	#	S
Percentage of the community connected	%	PD, S
occupation (formal and informal)	List, description	S
Education level	% at each level	S
Energy Access		
Number of customers	#	PD
Potential unconnected customers	#	S
Energy devices used	#	S
Lighting devices used	#	S
Appliance use	Total peak/average load drawn by appliances	SM
Sample appliance ownership by customer appliance type	Number and type of appliances owned	S
Household use of other fuels for lighting	Percentage use of other fuels for lighting	S
Household use of other fuels for cooking	Percentage use of other fuels for cooking	S
Energy access satisfaction	1-5 likert	S
Lighting device satisfaction	1-5 likert	S
Health, Education and Communication		
Schools connected	#	S
Schools with access to ICT	#	S
Hospitals or health centres connected	#	S
Average hours per night spent by children studying due to electricity access	hours	S
Number of children studying at home	#	S
Increase in access to health information	1-5 likert	S
Increase in access to local news	1-5 likert	S
Increase in access to international news	1-5 likert	S
Access to mobile and smart phones	Average # per household	S
Satisfaction with access to phones	1-5 likert	S
Number of injuries related to cooking, lighting or heating	# per year	S
Employment, Finance and PUE		
Average, highest and lowest household income	$/month	S
Average, highest and lowest household expenditure	$/month	S
Number of businesses and industries connected	, #, list and description of types	S
Perception of household financial security	1-5 likert	S
Average Business Income	$/month	S
Average business Expenditure	$/month	S
Household Access to credit or village savings and loan	% of customers	S
Household ownership of bank account	% of customers	S
Customer satisfaction of employment status	1-5 likert	S
Number of jobs provided by businesses connected	#	S
Energy cost savings made by businesses since electrification	$/month	S
Energy cost incurred by businesses since electrification (due to the addition of new machinery)	cost of new appliances, $/month	S
Business use of other fuels for lighting	Percentage use of other fuels for lighting %	S
Business use of other fuels for cooking	Percentage use of other fuels for cooking %	S
Increases in the number of products and services available in the local community	#, description	S
Female Empowerment		
Number of women with access to electricity	#, %	PD
Number of female owned businesses	#	S
Women's recreation and entrepreneurship: total number of women with possibilities to pursue both productive and recreational activities after nightfall	# or %	S

Female perception of electricity impact on: amount of free time	1-5 likert	S
Female perception of electricity impact on: recreational activities	1-5 likert	S
Female perception of electricity impact on: household responsibilities	1-5 likert	S
Female perception of electricity impact on: recreational activities	1-5 likert	S
Female perception of electricity impact on: level of tiredness	1-5 likert	S
Female perception of electricity impact on: Independence and decision-making power	1-5 likert	S
Perception of electricity impact on: respect within the household	1-5 likert	S
Female perception of electricity impact on respect within the community	1-5 likert	S
Female perception of electricity impact on: security in the home	1-5 likert	S
Tariff and Service		
General satisfaction with grid service	1-5 likert	S
Satisfaction with payment method	1-5 likert	S
Satisfaction with cost of electricity	1-5 likert	S
Perception of change in quality of life	1-5 likert	S
Perception of value for money	1-5 likert	S
Likelihood to recommend a friend	1-5 likert	S
Perception of payments being a burden	1-5 likert	S
Number of complaints	#	PD
Perception of increase in safety due to microgrid	1-5 likert	S
Electricity spend comparison	Average (Ideal spend – current spend)	S
Number of safety incidents	#/month	PD
Performance of the project against the service level agreement with customers	description	PD,S
Customer trainings on energy usage	#	PD
Perception of negative consequences of microgrid	description	S

7.4 Variables

7.5 Past and present minigrid projects in Malawi [17]

Name and Location of Mini-grid	Key Stakeholders And Funders	System description	End Users and Business Model	Status	Notes on Successful or challenging aspects
MEGA, Mulanje	MMCT, Practical Action SG, Sgurr	Hydro 80kW	Domestic	Active since 2014	Only breaks even after 5 sites are installed, heavily reliant on funding
SE4RC: Nyamvuwu, Chimombo in Nsanje district (30KW and 15 KW respectively) and Mwalija and Oleole in Chikwawa (55kw and 30KW)	PAC, CARD, FISD	Solar 55KW, 30KW,3OKW and 10KW	Domestic, Irrigation	Active since 2018	Improved access to modern energy services that has contributed to better well-being Enhanced community participation and skill transfer. Increased business operation hours and study time in the evening Crop production has increased through irrigation schemes
Sitolo , Mchinji	CEM, CES	Solar 80KW	Domestic	On-going implementation	Financed by UNDP, community participation, skills transfer commercialization and entrepreneurship development strategy.
Solar Villages Mini-grids, Nkhata Bay, Nkhotakota; Chiladzulu; Mzimba; Thyolo, Ntcheu	GoM	Hybrid (solar and wind) 35KW in all sites	Domestic	Non-operational since 2012	No community participation during implementation Lack of financial and business model No skills transferred to communities Lack of PUE activities
Likoma Island	GoM	Three diesel generators each rated 250kVA	Domestic and institutional	Still active with periodic power cut. 14 hour supply daily	The intermittent electricity supply affects medical care, education services, and the business sector leading to increased vulnerability of livelihoods. It is difficult to supply electricity to whole mainland for 24 hours daily because fuel consumption is higher. There is a need to integrate PV and wind electricity to reduce fuel cost
Usingini	PAC	Hydro (300KW)	Domestic and commercial	Ongoing project (still at implementation stage)	Financed by UNDP, community participation, skills transfer commercialization, and entrepreneurship development strategy
Mthengowathenga	Roman catholic Church	Solar Mini Grid (50KW)	Domestic and commercial	Active since 2017	Appreciable reduction of energy costs Reliable and sustainable energy In the hospital, which is connected to the public grid, longer power cuts appear almost every day. Supply but now the power cut has been minimised
ST Gabriel	Roman catholic	Solar-diesel Mini-grid (35KW)	Domestic and commercial	Active since 2017	The costs for public electricity and fuel for the two diesel generators a significant financial burden. Reliable 24 hours energy supply. Programmable, fully automatically working system, switching on and off, according to energy demand.
Nkhata Bay Hospital	GoM	Solar Mini Grid and solar Geyser	Institutional	Active since 2015	Programmable system automatically guarantees a 100% safe and uninterrupted energy supply with high ecological sustainability and economical use of the available energy sources.
Mthembanji Microgrid	United Purpose, University of Strathclyde	Solar Micro-grid (12kW)	Domestic and Productive Users	Installed July 2020	Successful business model relies on CAPEX funding, however smaller capacity means lower upfront costs

7.6 Customer segment energy demand assumptions

Appliance	**rating (W)**	**Time ON**	**Time Off**	**hours/day**	**# Appliances**	**Daily Energy (Wh)**
Household - low income						
Lights	5	18:00	21:00	3.00	4	60
Radio	5	18:00	21:00	3.00	1	15
Phone charging	5	18:00	19:00	1.00	1	5
					Total	**80**
Household - high income						
Lights	5	18:00	21:00	3.00	4.00	60
Radio	5	18:00	21:00	3.00	1.00	15
Phone charging	5	18:00	19:00	1.00	1.00	5
TV	75	18:00	21:00	3.00	1.00	225
					Total	**305**
Grocery Shop (no Fridge)						
Lights	5	18:00	21:00	3.00	4.00	60
Radio	5	07:00	19:00	12.00	1.00	60
Phone charging	5	07:00	19:00	12.00	2.00	120
					Total	**240**
Grocery Shop with Fridge						
Lights	5	18:00	21:00	3.00	4.00	60
Refrigerator	100	08:00	18:00	10.00	1.00	1000
Radio	5	07:00	19:00	12.00	1.00	60
Phone charging	5	07:00	19:00	12.00	2.00	120
					Total	**1240**
Barber Shop						
Lights	5	18:00	21:00	3.00	4.00	60
Radio	5	09:00	17:00	8.00	1.00	40
Phone charging	5	09:00	17:00	8.00	2.00	80
Shaving	15	09:00	17:00	8.00	1.00	120
					Total	**300**
Video Show						
Lights	5	18:00	22:00	4.00	4.00	80
TV	75	16:00	22:00	6.00	1.00	450
Stereo	50	16:00	22:00	6.00	1.00	300
DVD Player	20	16:00	22:00	6.00	1.00	120
Phone Charging	5	16:00	22:00	6.00	1.00	30
					Total	**980**
Church						
Lights	5	18:00	21:00	3	60	
Stereo	50	10:00	11:00	1	50	
					Total	**110**
School						
Indoor Lights	5	18:00	20:00	2.00	40	
Tablets	10.5	10:00	13:00	3.00	315	
Laptops	83.3	10:00	13:00	3.00	499.8	
					Total	**855**

7.7 Mapping the Malawi Ecosystem

A number of institutions contribute to the energy policy and regulatory framework in Malawi: the Ministry of Energy, including the Malawi Rural Electrification Programme (MAREP); the energy Regulatory Authority (MERA), the Electricity Supply Company (ESCOM), as well as a number of other Ministries, including Finance, Planning and Local Government. MERA evidences support for microgrids through the following statement: “MERA is committed to development of not only microgrids but the whole spectrum of renewable energy technologies, especially in the rural areas in order to complement Government’s policy on increasing access to modern and clean energy at national level” [292].

The National Energy Policy (NEP) (2018) recognises the limited impact of grid extension through the Rural Electrification Fund (REF) and accordingly provides for diversified use of REF to “significantly promote development of renewable energy microgrids in support of priority areas for rural electrification” [276]. The NEP provides other provisions relating to microgrids, including support for small-scale renewable energy initiatives by communities or entrepreneurs; capacity building in areas of Renewable Energy Technologies programming, supply and services, as well as in entrepreneurship and management, taking into account gender and social issues; promoting private sector driven renewable energy technology industry; and financing off-grid solutions, from the REF.

Microgrids are promoted in the NEP as one way of accelerating electrification in locations where grid extension cannot be an economically viable electrification approach [276]]. Based on the Malawi Renewable Energy Strategy (2017) [278], Malawi would have at least 50 operational microgrids by 2025. The mixed experiences of previous microgrids due to limited long-term support mechanisms has resulted in the development of legislation provisioning for microgrid support. MERA is mandated to regulate the energy sector and license energy undertakings in Malawi, and accordingly released the Malawi Minigrids framework in 2018 [281]. The framework aims to provide guidelines for the development and operation of microgrids in Malawi including: Solicitation process for microgrid development; Requirements for approval of microgrids project; Terms and conditions for registering or licensing; and Governance structures to ensure transparency and accountability in the operation of the microgrids. The framework also provides guidance on quality of supply and services standards for development and operation of the microgrids; Tariff methodologies and structures for microgrids to ensure sustainability of operations; and sustainability of microgrid operations if and when the national grid extends to the mini-grid supply areas.

Prior to the release of the new regulatory frameworks, Malawi suffered from a complicated regulatory environment unsuited to minigrid development. Figures from Regulatory Indicators for Sustainable

Energy (RISE) 2017 [322] show that on average it took between 1 and 2 years to obtain common permits to set up a minigrid facility in Malawi, and on average 120 days to obtain environmental clearance. Additionally, the cost of obtaining permits to set up a microgrid facility is the highest of all countries surveyed in the RISE report, with a quoted figure of $15,082. The new frameworks provide welcome removal of uncertainty and bureaucratic hurdles; however, their implementation is yet to transition to fully operational and further uncertainty is expected.

Capital for investment is a key challenge in Malawi as energy business models are not commonly understood by Malawian banks, and financial institutions tend to be risk averse with energy projects [288]. Interest rates in Malawi are extremely high, with banks regularly charging in excess of 40% [289]. Additional to these challenges, exchange rate fluctuations have impacted on renewable energy projects finances, especially when components are purchased from abroad. Some micro finance initiatives exist, evidenced by the existence of the Malawi Microfinance Network [290], but such organisations rarely allow enough capital to purchase a minigrid up front. Private sector investment for microgrids is limited in Malawi, with most energy related finance focused on the PSP and SHS, which has private equity and debt from local development banks providing working capital for enterprises.

Malawi’s weak economy constrains energy project financing, and as a result the majority of energy projects in Malawi have been funded by overseas donor grants [155]. Donor funding for energy projects receives criticism: some state that amounts are insufficient to achieve the government and SE4All targets for energy access in Malawi, while others complain of donor funding distorting markets and hindering private sector initiatives [217]. Despite increased awareness high potential social and economic impact of energy projects, they are still considered a relatively niche sector for donors in Malawi.

Government financial support for minigrid initiatives is limited, as the majority of its funding is dedicated to expanding rural electrification through the Malawi Rural Electrification Programme MAREP which primarily supports national grid extension; enabling the electrification of trading centres at a cost of c. 90 m MWK per trading centre [153]. MAREP has a facility for microgrid subsidy to reduce electricity tariff to customers but it has yet to be implemented on an operational project.

Despite emerging private sector pilot projects there are no proven sustainable business plans showing payback and return on investment for microgrid systems in Malawi. A key challenge to implementing robust business models is the generally low ability and willingness to pay of a customer base comprised largely of low-income subsistence farmers. In the short-term absence of subsidies, microgrid developers will face challenges to set tariffs that balance customer's low ability to pay with sufficient income for financial sustainability.

Another challenge is that of finding adequate and suitable Productive Uses of Energy (PUE) in rural areas of Malawi [155]. As has been seen in Phase 1 of this assessment, serving PUE reduces risk in the business model as any business relying on electricity to earn money are more likely to pay than domestic customers who are inherently risky customers to a minigrid operator. In Malawi there is generally a lack of rural businesses, unlike many areas of East Africa, where solar microgrid power commonly replaces existing diesel generators [294]. Maize Milling is common in rural areas of Malawi, however solar PV powered maize mills are still at pilot stage in Malawi.

In 2018 Scottish Government funding was awarded to Community Energy Malawi (CEM) build the capacity of a local management structure to run an innovative and sustainable solar powered minigrid with a commercial model to ensure the long term sustainability of a microgrid in Sitolo for supplying electricity to homes, schools and local businesses. The project will also build local enterprise capacity, skills and knowledge to enable the use of this electricity to stimulate local economic development and build community resilience, particularly among disadvantaged women, young people and among farmers (both men and women) [323].

Evidence suggests that most of the solar PV installations in Malawi are not working due to poor installation, lack of proper maintenance or inability to acquire new batteries [151]. Reasons for this include Malawi's general lack of appropriate technical skills to install, repair or maintain the systems and communities' low financial capacity to buy replacement batteries once the initial batteries' life span runs out [17]. Given the nascent status of microgrids in Malawi, human resources for microgrid development and implementation are similarly lacking at all levels. It has also been noted that capacity within the Malawian institutional setup to drive the sector seems inadequate [217]. Furthermore, the link between national planning and district implementation is constrained by lack of both human and financial resources [153].

Challenges exist in developing the wide ranging skill sets required to successfully develop microgrid businesses, including among others: negotiation, finance, contracting, regulations, technology, partnerships, planning, data and IT. Experience is similarly lacking in devising business models that can provide viable returns through provision of electricity to rural communities by balancing the high cost of operation, maintenance and administration with the returns from poor consumers with seasonal incomes that can afford only minimal amounts of electricity. Similarly, entrepreneurs suffer from a lack of knowledge about modern technology options, particularly recent innovations using hybrid systems, demand management and payment solutions.

This is being addressed in part through technical courses and Bachelor Degree courses being offered at Mzuzu University [324] that include techno-economic modelling of minigrids. Malawian technicians could benefit from attending international courses offered such as the micro-grid academy, part of the Institute of Energy Studies & Research-Kenya Power in Nairobi, which offers technical and entrepreneurial training programs on decentralized renewable energy solutions [325]. The district energy officer programme, led by CEM is providing some progress on energy related capacity building at a district level and could provide an opportunity for accelerating minigrid development through reducing capacity gap barriers [153].

Sustainable microgrid businesses benefit from use of mobile payment solutions to collect tariff fee payments rather than cash in-hand, ensuring transparency in reporting and accounting. The success of the existing initiatives evaluated was supported by high mobile network penetration and the availability of mobile finance platforms. In Malawi, mobile money operators including Airtel and Telecom have not yet reached a critical mass to allow cheap enough transaction fees for customers. Further challenges to uptake of mobile payment services in Malawi include mobile signal strength, coverage and reliability; high cost of metering and payment technology and platforms; risk of non-payment from customers and customer ability to pay; lack of experience with relevant business models and lack of technical knowledge and experience within communities [288].

Airtel transaction fees are applied on any withdraws from the account to another bank account. There is no charge to send money between phones but the cost to withdraw ranges from 2.5% to more than 5%, even for small transactions [326]. Additional operational costs for transporting cash out of the village to the central operator and/or banked for the cooperative/community are often non-trivial. As more customers sign up to use the service the transaction costs will reduce the service costs and make use of the service more affordable. In the short term, microgrid providers will rely on local vendors to collect cash payments from customers, which adds additional cost to the microgrid business for the wages of the vendor, and also adds risk of money going missing. As mobile money penetration increases and smart meters utilising mobile payments become viable these costs will reduce, increasing profitability.

Accessing components for microgrids (including generation, distribution, batteries, monitoring and control, payment platforms) is a challenge for project developers, and tests sustainability of systems with poor access to replacement parts. The few products found in Malawi are typically expensive compared to other countries in the region, and many manufacturers do not warrant their products if imported into Malawi. Whilst the Renewable Energy Equipment Project Waiver provided by the Malawi Revenue Authority [327] helps reduce cost, the small quantities of goods currently being imported on a project by project basis offer no economy of scale. VAT has recently been waived for solar panels, solar batteries, solar inverters, solar bulbs, solar regulators, solar chargers, solar accumulators, solar lamps, and energy efficient bulbs which is a benefit for project developers and finances.

Access to finance represents a challenge to all sizes of businesses in the country, relevant to both the mini-grid developers and operators as well as small businesses. Cost of credit in Malawi is also a prohibitive factor. Although the cost of credit, measured by the official bank lending rate, has fallen from over 40% to 13.5% since 2014, stakeholders reported typical lending rates above 20% and up to 100% for micro loans, making commercial debt unaffordable. Financing for off-grid solar products is only tentatively becoming available. Low mobile penetration rates in rural areas and high transaction costs are also hampering mobile payment options.

Beyond electricity supply technologies, availability of quality electrical equipment and appliances is limited for consumers in homes, enterprises and public facilities. Access to high efficiency products including light bulbs, TVs, and fridges is particularly important for rural consumers relying on systems with limited generating capacity. Despite standards on Solar goods imposed by the Malawi Bureau of Standards, substandard PV good regularly flood the market, reducing confidence in the technology [153].

An overview of the most pertinent energy policy and planning documents is provided Table 58.

Table 58: Policy context for renewable energy mini-grids in Malawi

Policy / planning document	**Relevance**
Energy Regulation Act, 2004	The Act established the Malawi Energy Regulatory Authority (MERA) that is mandated to regulate all energy activities in the country. In the electricity sector, MERA is responsible for issuing licences of generation, transmission and distribution and quality control of the electrical facilities. The planning, development and operation of mini-grid facilities are also under MERA jurisdiction.
Electricity Act, 2004 and Electricity (Amendment) Act 2016	The Electricity Act 2004 governs the activities of the electricity sector pertaining to generation, transmission and distribution. The Act, read together with the Electricity (Amendment) Act 2016, gave rise to the reform of the power sector resulting in the unbundling of the vertically integrated national utility and opening of the market to private sector participation including mini-grid operators. MERA developed electricity regulations to operationalize the Act. The regulations cover the planning, development, operation and maintenance of the generation, transmission and distribution facilities for electricity including mini-grid systems.
Electricity Act, 2004	The Electricity Act governs the activities of the electricity sector pertaining to generation, transmission and distribution. The Act gave rise to the reform of the power sector, the unbundling of the vertically integrated national utility and opening of the market to private sector participation including mini-grid operators. MERA developed electricity regulations to operationalize the Act. The regulations cover the planning, development, operation and maintenance of the generation, transmission and distribution facilities for electricity including mini-grid systems.
Rural Electrification Act, 2004	The Rural Electrification Act provides for the planning, development, operation and maintenance of rural electrification facilities. The Act defines (i) Management of rural electrification activities; (ii) Sources of funds for the rural electrification activities; (iii) Modes of electrifying rural areas; (iv) Installation of rural electrification facilities; (v) Operation and maintenance of rural electrification facilities; (vi) Subsidy provision for operation and maintenance of rural electrification facilities.

Policy / planning document	Relevance
	The planning, implementation and management of rural electrification activities fall under the auspices of the Ministry responsible for energy. The Act establishes the Rural Electrification Management Committee to, among others, (i) ensure that the majority of the Malawian population in peri-urban and rural communities have access to efficient, sustainable and affordable energy for their social economic development through grid extension and off-grid electricity supply (including solar home system technologies) and (ii) develop a rural electrification master plan and update it at regular intervals. The Committee is supported by the Rural Electrification Unit established in the Ministry of Energy. The master plan, covering a five-year planning horizon i.e. 2020 – 2025, has just been finalized. Rural electrification activities are funded from a ring-fenced Rural Electrification Fund (REF), capitalized from levies on energy sales. The Act allows for a subsidy under the REF to be available for off-grid solutions as well as for off-grid facilities to be operated on concession. Neither of these provisions have been operationalized as yet.
Malawi Nationally Determined Contribution (NDC), and the National Climate Change Management Policy (NCCMP), 2016	The NDC and NCCMP seek to promote climate change mitigation and adaptation for sustainable livelihoods through measures that increase levels of knowledge and understanding and improve human well-being and social equity, while pursuing economic development that significantly reduces environmental risks and ecological scarcities. In particular, the share of national greenhouse gas (GHG) emissions arising from the energy sector is anticipated to increase to 17% in 2040 compared to being only 4% in 2015. Renewable Energy is recognized as key to emission reductions.
Malawi Renewable Energy Strategy (MRES) 2017 – 2022	The Renewable Energy Strategy outlines interventions necessary to remove barriers for the planning, development, operation, maintenance, promotion and utilization of renewable energy technologies. It has also identified opportunities on the same. Clean energy mini-grids are identified as one of four priority areas to advance renewable energy in the country. The strategy targets at least 50 operational mini-grids in Malawi by 2025. MRES noted the need for the review of policy and regulations to create an enabling environment for clean energy mini-grids. This led to the review of the National Energy Policy and the development of the Mini-grid Regulatory Framework (refer below).
(Revised) National Energy Policy, 2018	The National Energy Policy targets an increase in access to affordable, reliable, sustainable, efficient and modern energy for every person in the country, aligning the country commitments with both the Sustainable Development Goal 7 and the Malawi Growth Development Strategy III (MGDS III). It outlines broad policy outcomes that include (i) Diversified energy sources; (ii) Developed and efficient energy sector; (iii) Modern and sustainable energy sources; (iv) Improved living standards for women and men due to equitable provision of energy sources; (v) Increased access to clean, sustainable and affordable energy for all people. The policy calls for private sector involvement in the electricity sector and, in concurrence with the Electricity Act, prompted the restructuring of the sector, including the unbundling of the vertically integrated national power utility and establishment of the Single Buyer and System and Market Operator to enable private sector participation in the market.
Mini-grid Regulatory Framework, 2020	The Mini-grid Regulatory Framework has been developed under the UNDP & GEF funded project called, ‘Increasing Access to Clean and Affordable Decentralized Energy Services to Selected Vulnerable Areas in Malawi’. The Mini-grid Regulatory Framework was formulated to facilitate the planning and development of mini-grid systems in Malawi in line with the National Energy Policy 2018 and MRES 2017-2020. It was published in July 2020 following a development process and extensive stakeholder consultation over 2 years. While being broad allowing for multiple scenarios of mini-grid development, ownership and delivery models, the framework does provide important, initial clarity to the market. It defines a mini-grid as an isolated system up to 5MW in size. It provides for systems smaller than 150 kW to be exempt from a license. It acknowledges the impact of grid arrival and provides some guidance for grid integration. It also allows for cost reflective tariffs, flexible tariff structures and subsidy options. It further includes guidance on selection criteria for mini-grids and technical and licensing requirements.
Environmental Management Act (EMA), 2017	The EMA requires that an Environment and Social Management Plan (ESMP) be developed for an energy project - including a mini-grid. The ESMP is required to adhere to (i) the Environmental and Social Impact Assessment (ESIA) guidelines for Environmental Impact Assessment (EIA) as well as (ii) Terms of Reference (TORs) that are provided by the Malawi Environmental Protection Agency (MEPA) after they receive a proposed project brief. The ESMP is used as a basis for managing, minimizing, mitigating and monitoring of the environmental and social impacts associated with the construction, operation, maintenance and decommissioning phases of the energy facility.

7.8 CAPEX costs inputs for piloted microgrids

	Mthembanji Cost	Kudembe Cost	Chosen Value	Lifetime
Solar PV Panels (USD/kW)	392.89	322.33	322.33	20
Solar PV Racking (USD/kW)	398.64	683.68	398.64	20
Generation installation (USD/kW)	205.42	107.87	107.87	-
Solar PV Inverter (USD/kVA)	286.00	221.75	221.75	10
Battery Inverter (USD/kW)	446.75	393.47	393.47	10
Storage (USD/kWh)	1,058.65	583.79	583.79	10
Distribution (cost per customer)	551.55	766.78	551.55	20
Customer Connections cost per customer	104.05	244.27	104.05	20
Smart Meters (per customers)	66.77	71.12	66.77	10
Distribution Installation	269.88	462.57	269.88	-
shipping container (fixed)	18,712	15,498	15,498	20
Fees and misc.	2,232	3, 955	2,232	-

7.9 SMSE business overheads

Item	USD/y	Notes
Staff		
Project Management	$ 23,389.58	MWK 24,839,731/y , taken from EASE
Field	$ 11,907.80	MWK 12,646,079, taken from EASE
Accountant	$ 11,381.65	MWK 12,087,309 Full time Accounts assistant/administrator
Supervision	$ 6,161.09	MWK 6,543,073, 10% of UP Energy programme manager salary
Technical Consultancy	$ 12,000.00	Minigrid expert: 24 days x $500 per day
Sub total	*$ 64,840.11*	
Admin Overheads		
Stationery and printing	$ 150.00	
IT and Internet	$ 1,500.00	$1000 per laptop per year, $500 software subscriptions
Office Rental	$ 1,500.00	Lilongwe office space
Communications	$ 250.00	Data and internet
Professional fees	$ 1,000.00	Audit, accountancy, legal
Sub total	*$ 4,400.00*	
Travel		
Vehicle running costs inc fuel	$ 5,062.15	160 km (Average round trip to a microgrid) x 0.14 l/km @2000MWK/litre 1 visit per month per minigrid
Motorbike running costs inc fuel	$ 1,807.91	160 km (Average round trip to a microgrid) x 0.05 l/km @2000MWK/litre 1 visit per month per minigrid
Vehicle maintenance	$ 5,000.00	Covers major repairs, assumes vehicle costs grant funded
Staff subsistence	$ 2,542	45,000 overnight allowance for half of trips
Sub total	*$ 14,412.43*	
Community Engagement		
Refreshments for participants	$ 5,000.00	2 meetings with refreshments per year per minigrid
Survey commission	$ 282.49	250MK commission per survey to site agents, conducted bi-annually
Sub total	$ 5,282.49	
TOTAL	*$88,935.02*	

7.10 Site Survey Data for business modelling at scale

Name of Village:	GPS_latitude	GPS_longitude	# residential customers	#Business total	#Institutions total	TOTAL
Chinkombero	-14.3034	34.42487	280	86	4	370
Chikuse	-14.1513	34.31966	198	121	4	323
Kalulu	-13.9979	34.1971	210	79	3	292
Tsoyo	-14.0803	34.15918	250	74	3	327
Mwambula	-14.4009	33.93775	120	37	1	158
Mthembanji	-14.2474	34.60702	51	7	2	60
Kudembe	-14.0003	34.19657	34	15	1	50
Kaname	-14.2393	33.96671	300	69	4	373
Hinda	-14.2567	34.21286	350	58	3	411
Ndindi	-14.292	34.627	200	21	3	224

7.11 Assumptions for Odyssey

Min. Renewable Fraction	100%
Min. Load Availability	90%
System Oversizing Factor	18%
System Losses	10%
Discount Rate	5%
What is the project's life span? (years)	20
In the beginning of which year do you expect to hit your baseline load?	2
load growth	2%
Annual Tariff Escalation	6%

7.12 Market Assessment techno-economic method assumptions, justifications and limitations

Assumption	Justifications and limitations
Blantyre and Lilongwe are the only maintenance hubs in Malawi	All 17 Solar Energy vendors in the online Malawi YP business directory are in either Blantyre or Lilongwe [328].
Any off-grid installation is served by the closest maintenance provider	In the accessibility mapping methodology, the shortest travel time to Blantyre or Lilongwe is calculated, meaning that it is inherently assumed that the travel times are calculated for the nearest of the two. Ideally this would be the case, but in reality an operator may be based in the more distant maintenance hub in certain cases.
All solar PV panels are installed at the optimal angle for the installation's latitude	On a site specific basis, it is standard practice to optimise the tilt-angle of each PV unit based primarily on the latitude of the site.
Diesel is obtainable only from Malawian towns and cities	Puma Energy has 62 fuel retail sites in Malawi [329], mostly in urban areas. This assumption might not be consistently justifiable however, as fuel shortages have been relatively common in Malawi in recent years. Additionally, a black market for fuel exists, but considering this is beyond the scope of the study.
Diesel is obtainable at a price of 890.9MK/L	Maximum pump price of Diesel for Malawian retailers was 890.9MK/L at time of modelling [330] .
Daily variation in Solar Resource and temperature is uniform across Malawi	As a relatively small country, the daylight hours at the far north and far south of the country will be only slightly different due to the difference in latitude.
Temperature Data from World Clim V2 [218] is representative of the current climate in Malawi.	This data may be increasingly inaccurate due to the effects of climate change. The data is based on historical measurements for 1970-2000. Aside from an increased temperature, microclimates apparent in the data may no longer be representative of reality.

Travel times for Diesel deliveries or Maintenance are by the fastest route and assume constant travel from origin to destination.	The accessibility mapping methodology, used as is, provides the shortest possible time for journeys. It may be that certain journeys require alternate routes or breaks in travel, adding to the travel time.
Grid extension is motivated by the least cost electrification of households	Grid extension is highly politicised and often not rolled out in a manner purely informed by economic trade-offs.
Any household within the grid and lights exclusion zone is best served by grid extension, or is currently served.	As a result this study makes no consideration of so called ‘under the grid’ populations, which may in reality be a significant market for off-grid provision.
Household density thresholds are calculated on the basis that radial grids cease to be viable once the distribution line exceeds 500m	This may not be equally valid for low, medium and high capacity micro-grids. Additionally, the individual site topography and population distribution will dictate what lengths of radial distribution are feasible.
Areas best served by the grid are considered as existing solely within the grid and lights exclusion buffer.	In reality grid extension considerations are complex, and should account for topography, population densities, cost of installing substations, distance from existing substations, existing grid constraints and grid stability. These considerations are, however, beyond the scope of this study.
Micro-grid systems are more cost-effective and suitable for electrification than stand-alone systems above the given household density threshold.	There is a degree of uncertainty surrounding the tipping point between stand-alone and micro-grid preference, and as this methodology does not directly address this or make comparisons, it may be the case that in locations of relatively low population density, standalone systems are preferable to the low capacity micro-grid.

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