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PAPER

Understanding solar minigrid sustainability and impact through a holistic key performance indicator framework

Aran Eales[1,*], **Elizabeth Banda**[2], **Damien Frame**[1] **and Scott Strachan**[1]

[1] University of Strathclyde, 16 Richmond St, Glasgow, United Kingdom
[2] Self Help Africa Malawi, PO BOX, B-495 Lilongwe, Malawi
[*] Author to whom any correspondence should be addressed.

E-mail: aran.eales@strath.ac.uk

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Abstract

Despite increasing global electrification rates, over 700 million people remain without access to electricity, predominantly in Sub-Saharan Africa. Solar minigrids offer a promising solution for rural electrification in areas unlikely to be connected to the national grid. However, existing evaluations of minigrid projects often overlook holistic performance, particularly the social impacts on the communities they serve. This study aims to fill this gap by proposing a novel key performance indicator (KPI) framework that integrates technical, economic, and social metrics, providing a comprehensive assessment of minigrid performance. The research question guiding this study is: How can a holistic KPI framework enhance the understanding of solar minigrid sustainability and impact? To address this, KPIs were designed through a systematic process involving a literature review, stakeholder engagement, and validation through a case study minigrid in Malawi. The framework was applied using data collected from smart meters, remote monitoring, and enumerator surveys. Key findings reveal that while technical performance was robust, economic sustainability requires further optimisation, and social impacts, particularly on gender and community well-being, were significant. This study demonstrates the importance of a balanced evaluation framework that considers all dimensions of minigrid performance. By adopting such a holistic approach, minigrid developers, policymakers, and investors can make more informed decisions, ultimately improving the sustainability and effectiveness of rural electrification projects.

1. Introduction

The last decade has seen global electrification rates increasing from 83% to 89%, yet over 700 m people still lack access to electricity [1]. By 2030, it is estimated that 650 million people will remain without access, with 90% of these in Sub-Saharan Africa (SSA). This challenge is highlighted by the united nations sustainable development goal (SDG) 7: access to clean, reliable, and affordable Energy and is being addressed by the united nations sustainable energy for all initiative [2], but the problem inherently demands new and innovative technical and business solutions for rural electrification.

Solar minigrids have emerged as resilient community infrastructure that offers a secure and affordable route to energy access for communities unlikely to obtain a grid connection in the near future. Understanding the technical, economic, and social impact performance of solar minigrids is key to informing system design, business modelling, and community engagement strategies to improve their sustainability, reduce costs, and accelerate deployment.

Despite recent growth in solar minigrid projects, there remains a significant gap in research regarding their holistic performance, particularly concerning social impacts on the communities they serve. Existing key performance indicator (KPI) frameworks generally focus on technical and economic parameters, preventing a deeper, nuanced understanding of their sustainability and impact.

This paper addresses this gap by proposing a novel KPI framework that incorporates technical, economic, and social impact metrics, allowing for more holistic insight into minigrid performance and the impact experienced by communities. The research question guiding this study is: How can a holistic KPI framework enhance the understanding of solar minigrid sustainability and impact? To answer this question, the framework is applied to a case study minigrid in Malawi, utilising data collected from smart meters, remote monitoring, and enumerator surveys.

The structure of this paper is as follows: The next section presents a literature review which delves into existing research and identifies barriers to effective minigrid deployment and embeds the contribution of this paper in the academic status quo. Following this, the proposed holistic KPI framework is introduced and applied to a case study in Malawi. The results of the framework application are then presented and discussed, highlighting the technical, economic, and social performance and impact of the minigrid. Finally, a discussion section explores implications and highlights limitations of the KPI framework as well as providing recommendations for improved technical design, business modelling, and policy to scale solar minigrids as resilient community energy infrastructure.

1.1. Barriers to advancing community energy for poverty reduction with solar minigrids

Energy poverty constrains economic growth, handicaps the development of self-sufficient local communities, and threatens security [3]. Pathways for electrification include national grid expansion to connect populations through centralised electrical grids; and off-grid solutions such as pico solar systems (PSP), solar home systems (SHS), and minigrids/microgrids [4]. Grid expansion solutions employed in urban locations with dense population incur high capital investment but are traditionally most reliable with lowest energy cost [5]. Remote and rural communities consume significantly less energy per capita than urban populations, which coupled with low population density and long distances to the grid, make grid expansion cost prohibitive [6]. Energy poverty is highest in these remote areas, where in SSA only 31.5% of the rural population have access to electricity compared to 78.1% of urban populations [7], highlighting the crucial challenge of SDG7 to connect these last mile communities.

Minigrids are defined as a set of electricity generators and energy storage systems interconnected to a distribution network supplying electricity to a localised group of customers [8]. Due to their geographical constraints and the nature of the customers or users they serve they can be considered as resilient community energy systems. Minigrids offer the most economically viable off-grid rural electrification solution for 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 [9]. It is estimated that to achieve the 2030 electrification goal for remaining rural locations, at least 210 000 new minigrids need to be employed serving 490 million people and requiring a total investment of more than $220 billion [10]. The global market for minigrids with solar photovoltaic (PV) generation is growing, due in part to decreasing costs of solar PV modules, battery storage and ancillary components [11]. Solar PV offers low carbon generation, a modular and scalable approach to system growth, low maintenance and is specifically suited to SSA's high solar resource. The solar minigrid market in Africa is growing, with companies such as Husk Power [12], PowerGen [13] and SteamaCo [14] advancing innovation in technology for minigrid metering, monitoring and control as well as business models and tariff setting.

The success of solar minigrid operators depends on their ability to address the energy trilemma: security, affordability, and sustainability, all of which contribute to community resilience and must incorporate social acceptance. However, several barriers hinder the successful achievement of these aims. One significant barrier is poor planning, which can result in high energy costs surpassing the community's willingness to pay, reduced connections, and oversizing or undersizing of systems. These reasons, as well as failure to incorporate the minigrid into the local economy, inability to provide local support through the minigrid lifecycle; and failure to stimulate income-generating uses of electricit, can lead to project failures [15–17].

A socio-techno-economic approach that integrates robust monitoring and evaluation frameworks is essential to address these issues. Performance monitoring has several benefits for multiple stakeholders in the minigrid sector. For developers, demand forecasting for current and future minigrids 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, operation and maintenance 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. Minigrid 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 minigrid scaling [18].

Current monitoring frameworks often focus narrowly on technical and economic parameters, neglecting social aspects critical for holistic planning and sustainable implementation. Holistic planning tools and methodologies encompassing socio-economic impacts of minigrids on the local community to inform decision-making and enable the successful design and implementation of solar minigrids 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 [19]. A growing body of literature highlights the limitations of the current binary indicators of energy access [20–22]. The ESMAP Multi-Tier Framework (MTF) [23] 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 [24]. 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 [24]. 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 [25], 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 [26], and can include both positive and negative effects.

Minigrids hold potential to contribute to several SDGs through fostering socio-economic development in rural areas by raising standards of welfare, education, health care, and technology [25, 27, 28]. 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 [29]. There is currently little documented evidence of the specific effects minigrid systems have on social infrastructure, community resilience, or general well-being of communities served, with reporting typically focusing on monitoring the technical and financial performance, often prioritising financial metrics such as rate of return on the initial capital investment [28]. While measuring a project's social impact is acknowledged by stakeholders as a motivating factor, developers frequently do so insufficiently [28] 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 [30]. Social return on investment (SROI) is well established in social enterprise economics as a method [31] for translating social value to monetary value and the SROI method has been applied to micro-hydro demonstrator projects [32] and solar energy solutions for schools and health centres in Kenya [33]. SROI is just one of many methods and frameworks designed to measure social impact [34], but all require careful design of what to measure and identification of appropriate indicators [35].

A comprehensive literature review carried out by the authors [28] found that despite general acceptance of the benefits of rural electrification through mini-grids, there is a lack of empirical evidence on their social impacts, highlighting the need for better-integrated monitoring and evaluation methodologies that focus on social impact, beyond technical and economic performance. Serval academic studies have developed specific technical KPI frameworks [36–38], while others have explored the sustainability of minigrid projects through multiple indicators [39, 40] or purely focuses on social and economic impact of minigrids [32, 41]. Industry and practitioner studies have been found to focus primairly on economic indicators to drive investment in the sector [42, 43]. While some studies advocate that measuring minigrid 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 [30, 44] none could be found that present a comprehensive techno-socio-economic KPI frameworks to better understand how specific interventions in technical design and business model can better serve the minigrid community.

In summary, while technical and economic metrics are crucial, they are insufficient alone to capture the full impact of solar minigrids. 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 minigrids to be maximised—improving future minigrid designs and business models. A comprehensive framework that also includes social impact metrics is essential to understand and enhance the sustainability and effectiveness of minigrids in reducing energy poverty and fostering community development, which is the motivation behind the contribution of this paper.

2. Holistic KPI framework design for solar minigrids

2.1. Development of the KPI framework

The development of the KPI framework is a systematic process that involves identifying the key metrics necessary to evaluate the technical, economic, and social performance of solar minigrids. The framework is designed to provide a comprehensive understanding of minigrid sustainability and impact, which is critical for practitioners who aim to develop customised frameworks suitable for their specific contexts. The process of developing the framework includes several stages:

1. **Literature review and benchmarking**: initially, a thorough review of existing KPI frameworks and performance metrics used in the minigrid sector was conducted. This included analysing academic literature, industry reports, and existing case studies to identify common indicators and gaps in current monitoring practices.
2. **Stakeholder engagement**: input was gathered from various stakeholders, including minigrid developers, operators, community members, policymakers, and investors. This engagement helped identify the practical needs and concerns of different stakeholders and ensured the framework's relevance and applicability.
3. **Identification of** KPIs: Based on the insights from the literature review and stakeholder engagement, a list of potential KPIs was compiled. These indicators were categorised into technical, economic, and social metrics, ensuring a holistic approach to performance evaluation.
4. **Theory of change (ToC) development**: the ToC underpins the KPI framework by outlining the desired outcomes and the pathways to achieve them. It specifies the key changes the minigrid project aims to make, identifies all possible outcomes and outputs, and highlights activities that must be undertaken to achieve these goals.
5. **Framework validation and refinement**: the initial set of KPIs and the ToC were validated through pilot testing on a case study minigrid in Malawi. Feedback from this pilot was used to refine the indicators and the framework to ensure they were practical, measurable, and aligned with the project goals.

2.2. ToC

Minigrid performance and impact is measured through the implementation of a ToC 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 [45]. 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. KPIs are quantitative or qualitative techniques used to compare components at each level of the ToC, track the development of the activities involved, and evaluate the scope and pace of progress of a desired goal [30]. Used as part of a monitoring, evaluation and learning strategy, they can track the performance of a minigrid in technical, economic and social realms. Literature on best practice for KPI frameworks utilised on mini and minigrids is common [18, 37, 38, 46]; however, most focus on technical and economic parameters. The KPI framework described here maintains that common techno-economic metrics used in the industry [18, 37] should be applied, but places more emphasis on applying metrics monitoring social impact that map to the SDGs. The ToC for the KPI framework is designed to guide the systematic evaluation of the minigrid's performance and impact. It is structured around three main outcomes: technical reliability, economic viability, and social impact. Each outcome is linked to specific outputs and activities as described in table 1.

2.3. Choosing KPIs

The proposed framework does not attempt to provide an exhaustive list of all possible indicators that could be applied to any given minigrid development, instead the framework provides guiding principles illustrated through application to a case-study in Malawi.

2.3.1. 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 minigrid 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.

Table 1. Theory of change used to develop the KPI framework.

	Outcome	Outputs	Activities
Technical reliability	Improved system reliability and reduced downtime.	Enhanced monitoring systems, regular maintenance schedules, and rapid fault response mechanisms.	Implementing smart meters and remote monitoring, training local technicians, and establishing maintenance protocols.
Economic viability	Sustainable financial performance with positive cash flow.	Increased revenue from electricity sales, optimised operational costs, and effective tariff structures.	Conducting demand assessments, promoting productive uses of energy, and engaging in regular financial monitoring and reporting.
Social impact	Enhanced community well-being and improved quality of life.	Increased access to electricity, improved health and education services, and higher levels of community satisfaction.	Conducting baseline and follow-up surveys, facilitating community engagement sessions, and promoting gender-inclusive practices.

Demand in previously unconnected rural areas is uncertain, which can lead to minigrid 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 minigrid 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 [47] 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. The choice of Renewable Ninja over more commonly used tools like HOMER and PVsyst is justified by its ability to provide high-resolution, site-specific weather data and its cost-free accessibility. Renewable Ninja allows for hourly simulations of power output from wind and solar plants worldwide, utilizing weather data from NASA MERRA reanalysis [48] and CM-SAF's SARAH dataset [49]. These capabilities ensure accurate energy production estimates, tailored to the specific climatic conditions of the study site, making it an ideal tool for reliable performance evaluation and planning in remote areas.

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 minigrids to reduce capital costs e.g. in the case of a low utilisation rate.

2.3.2. Economic performance

Minigrid financial sustainability, direction of tariff modifications, and development of suitable business models for future minigrids 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 [50]. Analysis of electricity sales income also allows for detailed design of scaled operations where a portfolio of minigrids is deployed: the more revenue data available, the more detailed financial forecasts can be made [50]. Seasonal trends can be discovered through analysis of differences in the monthly minigrid income over the course of a particular year. Average revenue per user (ARPU) per month is a common metric used to evaluate financial performance, that is of particular interest to investors. Monthly revenue totals for the entire minigrid 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. Capital expenditure (CAPEX) and operational expenditure (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 minigrid economic performance to benchmarking, and offer essential metrics to share with donors and investors and use for business modelling at scale. To further inform tariff setting and enhance financial assessments, levelized cost of energy (LCOE) can also be included as an economic indicator. LCOE provides a comprehensive measure of the average cost per unit of electricity generated, factoring in total costs over the system's lifetime, and helps determine economically viable tariffs for minigrid projects.

2.3.3. Social impact

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 SDGs. Although monitoring these KPIs provides insight into changes happening within the minigrid community, direct attribution is not always possible due to the multiplicity of internal and external factors that affect local socio-economic development.

2.3.3.1. Demographics and gender equity

Demographic questions seek to 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.

Minigrids have the potential to contribute to SDG10, to achieve gender equality and empower all women and girls [51]. It has been shown that women can benefit significantly from having a reliable access to energy [52], 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 [53]. Studies have shown that electricity access can be 'gendered', providing men and women with different opportunities and benefits from electricity access [54]. 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 [55]. 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 minigrids impact on their lives.

2.3.3.2. Energy access (SDG7)

Understanding minigrids contribution to national SDG7 targets includes tracking number of customers, with potential unconnected customers as a number and percentage also tracked. Recording numbers of energy consuming devices and methods of lighting monitors 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 measured. Monitoring how the minigrid affects local cooking practices can also be incorporated, however solar minigrids generally do not power electric cooking devices apart from some small scale pilots [56].

2.3.3.3. 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 [57]. Minigrids offer positive impacts on health and monitoring health-related metrics enables understanding on health impacts and associated improvements in quality of life. KPIs tracking access to health centres, access to health information, and reduction in burns injuries (for minigrids offering eCook) tracks health impact related to the minigrid.

Access to health information increases awareness and understanding of common illnesses and diseases, and enables informed decision making to prevent them. The increase in access to health information in the minigrid community can be attributed to several factors directly and indirectly influenced by the minigrid installation. Reliable electricity enables the use of electronic devices such as radios, televisions, and mobile phones, which are primary sources of health information. It also supports the operation of health centers and clinics, facilitates mobile phone use for accessing health resources, and creates opportunities for health education through community gatherings and workshops. These factors combined enhance the community's ability to receive and benefit from vital health information, thereby improving overall health outcomes.

Education is fundamental for growth, productivity, and development within communities; it is foundational for family welfare; and it provides people with essential political knowledge [58]. 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 [38]. 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 minigrid electricity. Further qualitative monitoring can be conducted through informal interviews with head teachers to ascertain minigrid impact on school learners, or tracking pass rates, although the latter is difficult to attribute directly to the minigrid.

Literature suggests that access to information and digital communication contributes to increased social and economic development [59, 60] states that access to information and communication contributes to development in the broadest sense as well as the expansion of human freedoms, while [61] 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 minigrid 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.

2.3.3.4. 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 [62, 63] 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 minigrid 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.

2.3.3.5. Tariff & service (SDG 9)

[64] 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.

2.4. Data collection

This section describes the instruments and techniques available for gathering technical, economic, and social impact data, namely smart meters, remote monitoring, surveys and project management documentation. Specific techniques utilised in the case study are detailed in section 3.

Smart meters, often discussed in the context of a smart grid [65], serve as a home’s interface between the smart grid, the utility company, and the rest of the home’s electrical demands. Smart meters designed exclusively for solar minigrids 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.

Remote monitoring systems (RMS) allow observation of off-grid energy systems from a distance, with the majority of currently available minigrid RMS tracking 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 [66]. Similar to smart meters, most RMS provide data download through customised web portals.

Through face-to-face surveys with minigrid customers, trained enumerators utilising smart phones collect 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 [30]. A baseline survey conducted during the pre-installation phase gives a complete picture of community’s demographics, energy use, and quality of life, with subsequent follow-up surveys conducted periodically to track impact, ideally every six months.

Table 2. Mthembanji minigrid component specifications.

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

Project implementation records, such as meeting minutes, budgeting spreadsheets, invoice repositories, and project diaries provide access to valuable qualitative and quantitative data to track KPIs.

3. Minigrid case study in malawi

Malawi is one of the world's poorest countries, and efforts to reduce poverty are constrained by the country's low levels of electrification rate of 14% in 2019 [67]. With cost decreases in solar PV components and Malawi's abundant solar resource, the establishment of solar PV minigrids is being explored, especially in regions unlikely to get a main grid connection imminently [68]. Solar minigrids are estimated to be the lowest cost energy access route for 37% of the population [69], and the market potential for small, densely populated villages more than 5 km from a grid connection is estimated to be over 4.5 million, or 27% of the population [70]. However, effective and sustainable business models that are financially feasible while also meeting the social development objectives of the rural communities they serve are needed to implement solar minigrids on a large scale.

The Mthembanji minigrid in the Dedza district of Malawi, was installed in 2020 through the Scottish Government EASE project [71] and serves 60 customers for domestic and commercial use. The system comprises a central generation unit with solar PV panels, AC inverters, lithium-ion batteries, and auxiliary electronic components housed in a shipping container, outlined in table 2. The distribution grid provides 240 V single-phase power through overhead wires with smart meters managing customer payments via a site agent. The minigrid is owned and managed by local partner Self Help Africa Malawi through a social enterprise framework, ensuring a reliable service is offered to the community.

3.1. Justification of methodology and case study selection

The selection of the case study in Malawi is justified based on several factors. Malawi is one of the world's poorest countries, with one of the lowest electrification rates. The country's abundant solar resource and the decreasing costs of solar PV components make it an ideal location to explore the implementation of solar minigrids. The chosen site, Mthembanji in Dedza District, is representative of many rural areas in SSA where grid expansion is unlikely in the near future. Although an opportunistic approach through the involvement of the Authors in the project, studying this site provides valuable insights that can be generalised to similar contexts.

The methodology of this case study employs the novel KPI framework to evaluate the technical, economic, and social impacts of the minigrid. Combining quantitative data from smart meters and remote monitoring with qualitative data from enumerator surveys, this mixed-methods approach ensures a comprehensive understanding of minigrid performance and community impact. The insights gained inform recommendations for improved technical design, business modeling, and policy development, supporting the broader goal of scaling solar minigrids as resilient community energy infrastructure.

3.2. Case study indicators and data collection

Technical, economic and social impact KPIs monitored for the Mthembanji minigrid are listed in table 8 and table 9 in the appendix. The technical indicators monitored include system outages, generation patterns, battery health, and customer segment demand. Economic indicators focus on sales revenue, cost per connection, and total cost of power. Social impact indicators cover demographics and gender equity, energy access, health, education, communication, and employment.

Regarding technical indicators, renewable energy penetration (100% at all times) and the amount of fuel consumed (zero for all times) have not been included. Voltage imbalance, voltage variations, and frequency variations can be considered for a more thorough analysis, as can battery current and efficiency, average power and maximum power. Regarding economic metrics number of new connections and disconnections per month can be tracked but are not included for this study as both are zero. Other revenue (e.g. from other services offered, monthly service charges, or connection fees) can also be included but have been omitted for

Table 3. Data collection methods used in the case study.

Data Collection method	Tool/Source	Description
Smart meters	SteamaCo [14]	Real-time data on sales, demand, and smart meter uptime accessed through a cloud platform
Remote monitoring	SMA sunnyportal [72]	Remote monitoring of generation and storage data accessed through Sunnyportal accessible for weekly or daily download and logged at 5 min intervals
Temperature	Bespoke	Internal, external, and battery temperature, logged at 10 min intervals and transferred to a cloud platform using the site's 3 G Wi-Fi network
Surveys	KoboCollect [73]	'Customer journey' surveys for all minigrid customers (n = 60) gathered through enumerators
Project records	EASE project partners	For economic metrics including CAPEX and OPEX

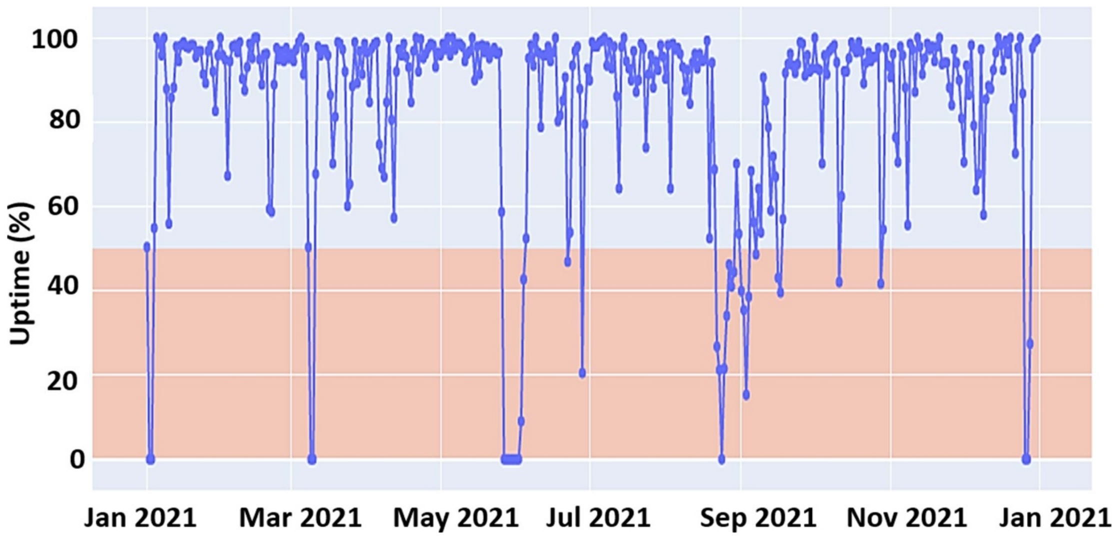


Figure 1. Daily communication uptime 2021.

this study. LCOE was not included in this analysis due to the focus on short-term financial metrics that were immediately relevant to the project's early operational phase and the specific data available at the time. Data collection methods for the case study are outlined in table 3.

4. Results

KPIs monitored at the Mthembanji minigrid are described in technical, economic, and social impact themes, with performance data presented and specific implications for technical and business design of minigrids highlighted, while relevance to policy and the wider minigrid ecosystem are discussed in section 4. All data is available through an online data visualisation platform hosted by the EASE project [74].

4.1. Technical indicators

4.1.1. System outages

SteamaCo data in figure 1 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). Smart meter downtime means the system cannot take payments and customers cannot top up their accounts leading to customer dissatisfaction. Disaggregation between smart

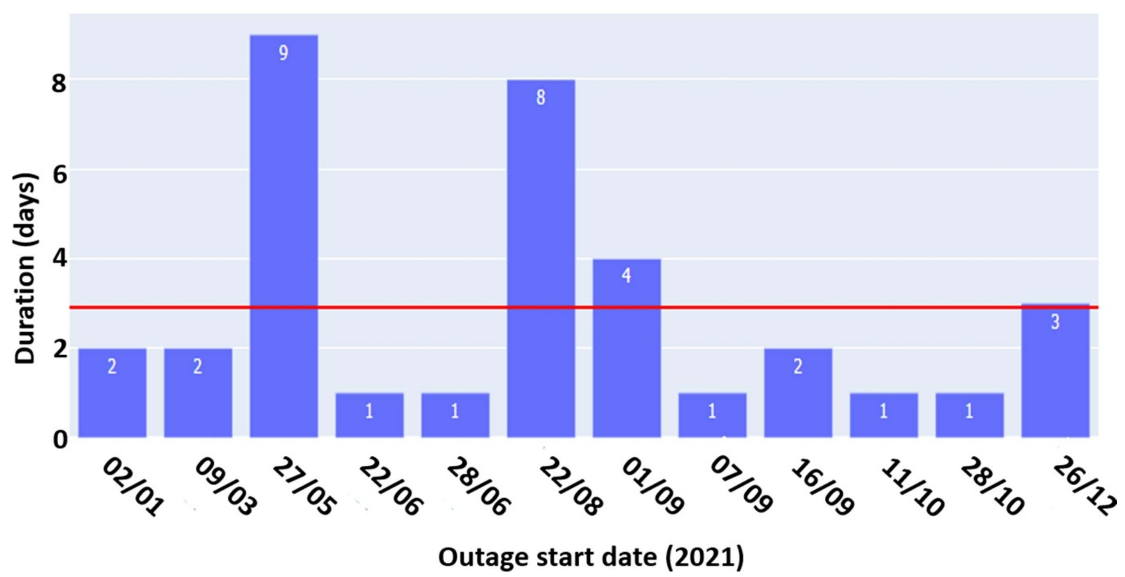


Figure 2. Start date and length of outage for 2021.

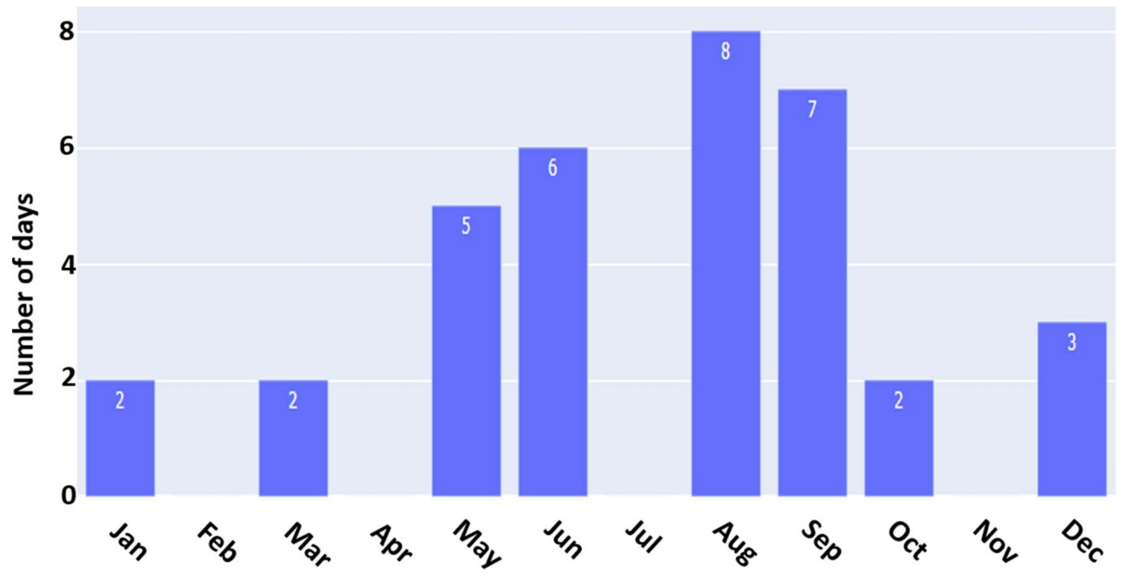


Figure 3. Number of days of outages 2021.

meter and generation downtime is not feasible under the current system of data collection. Figure 2 shows start date and length of outages for 1 year, revealing 12 outages in 2021, lasting an average of 2.8 d per outage. The number of days in each month where an outage was discovered is shown in figure 3. With only four months having no interruptions, August and September had the most outages (8 and 7 d, respectively). Resolving smart meter outages necessitates travel to site by technicians, coordination with international support teams, and in some cases replacement of components such as antennae. The frequency of and time to rectify these issues reflect the nascent state of the technology and a crucial area for improvement.

4.1.2. Generation

Figure 4 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 [75]. 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 7293.9 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 minigrid performance, allowing greater insight for futureproofing systems.

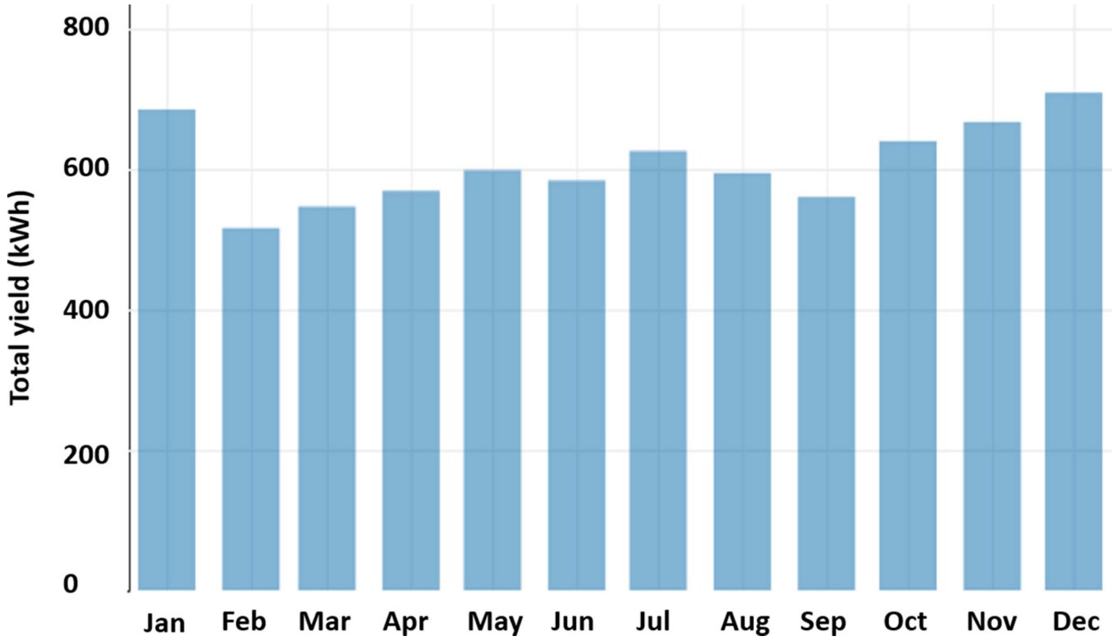


Figure 4. Mthembanji monthly generation 2021.

4.1.3. Battery health

4.1.3.1. State of charge

Battery state of charge and power flow for a typical day in July is shown in figure 5. 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 (there are no street lights connected to the minigrid). 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 nighttime loads are correct, with the depth of discharge reaching the recommended limits of 80%.

This contrasts to figure 6, 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 nighttime power available.

Figure 7 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 4. 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.

4.1.3.2. Battery temperature

Temperature logging revealed battery temperatures reaching over 35 °C soon after the logger was installed in April 2022, as shown in Figure 8. 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

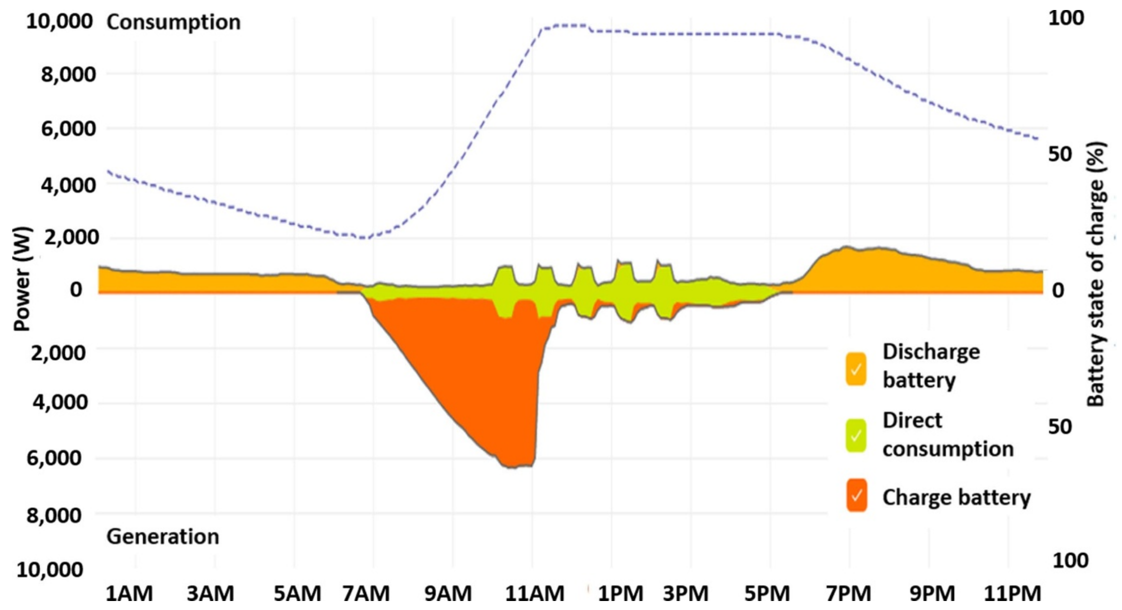


Figure 5. Battery state of charge and power drawn by battery, 10/7/21.

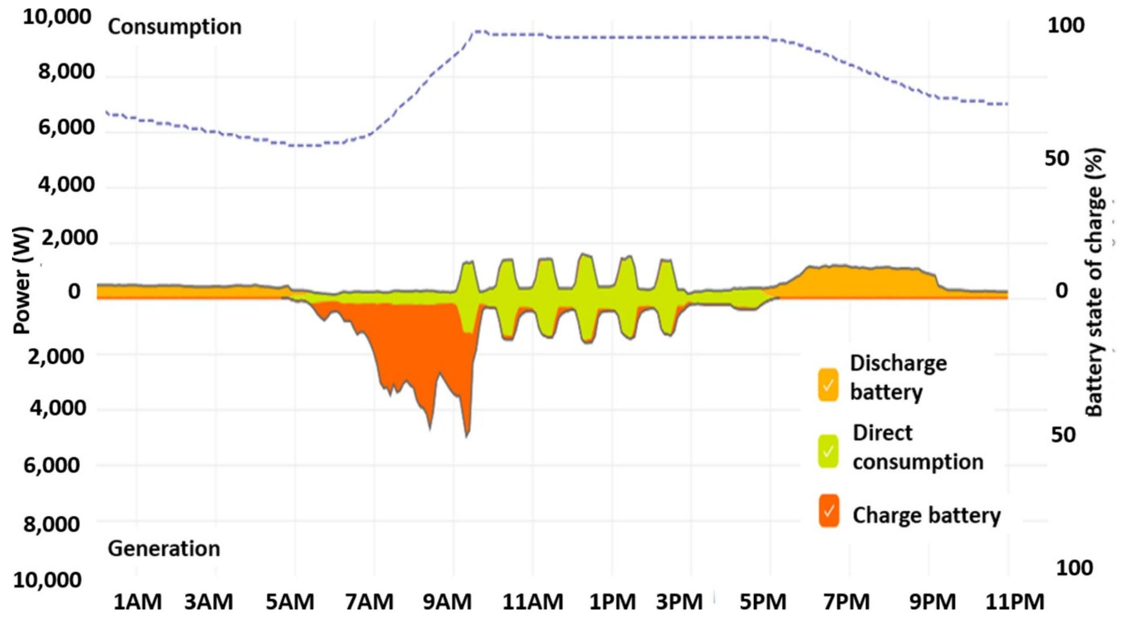


Figure 6. Battery state of charge and power drawn by battery, 13/02/21.

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.

4.1.4. Customer segment demand

Figure 9 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 10, 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

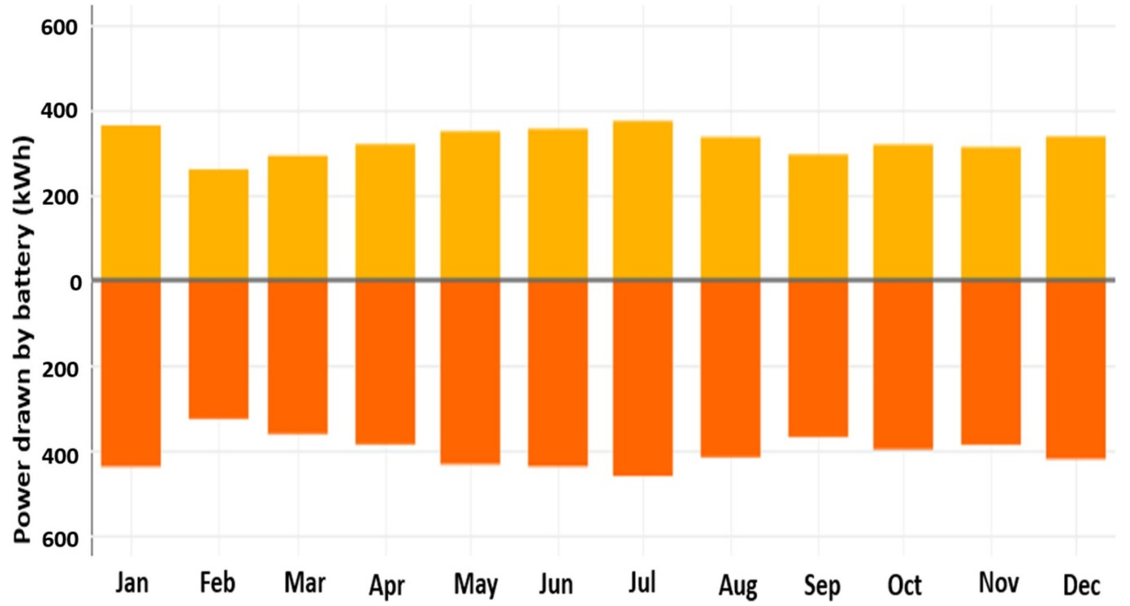


Figure 7. Monthly total battery charge/discharge power (kWh) for 2021.

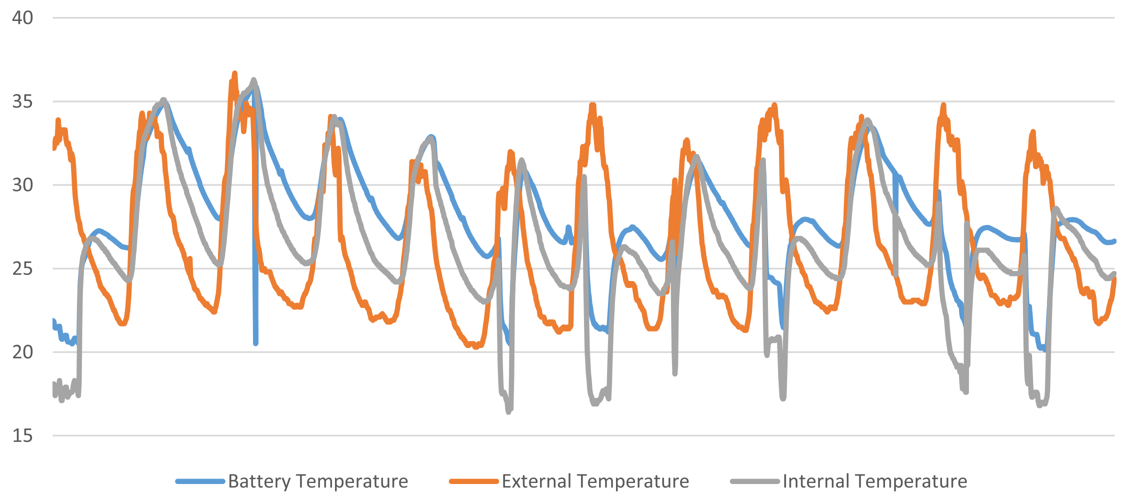


Figure 8. Battery temperature, external temperature and internal temperature, 10 min intervals for 10 d in April 2022.

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.

Load profiles gathered from SteamaCo data for total minigrid demand disaggregated into customer segments is shown in figure 11, 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 12 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 minigrid design.

4.1.5. Utilisation rate

Inputs and calculations for this process are summarised in table 4, revealing a noticeably low utilisation rate of 21.6% and indicating that significant excess energy in the system is being wasted. A key challenge for any minigrid 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 that align

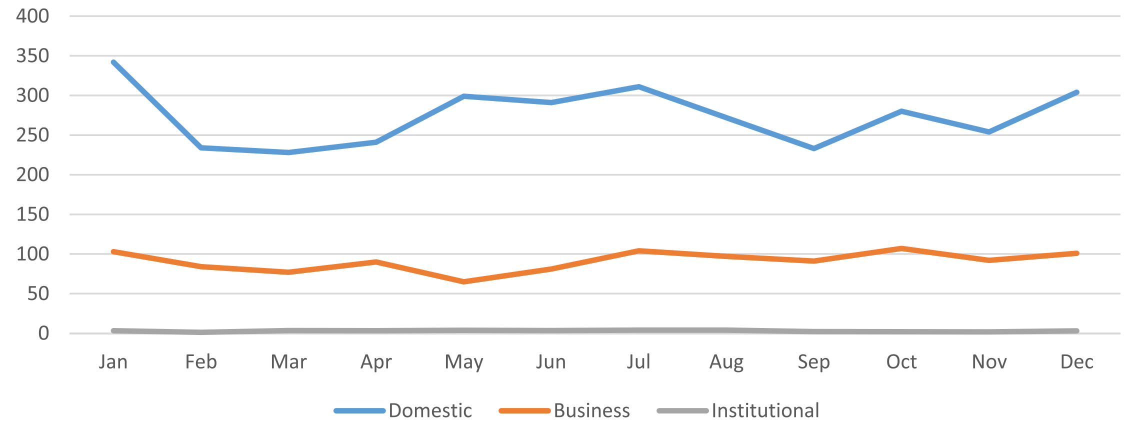


Figure 9. Total monthly demand for 2021 per customer segment (kWh).

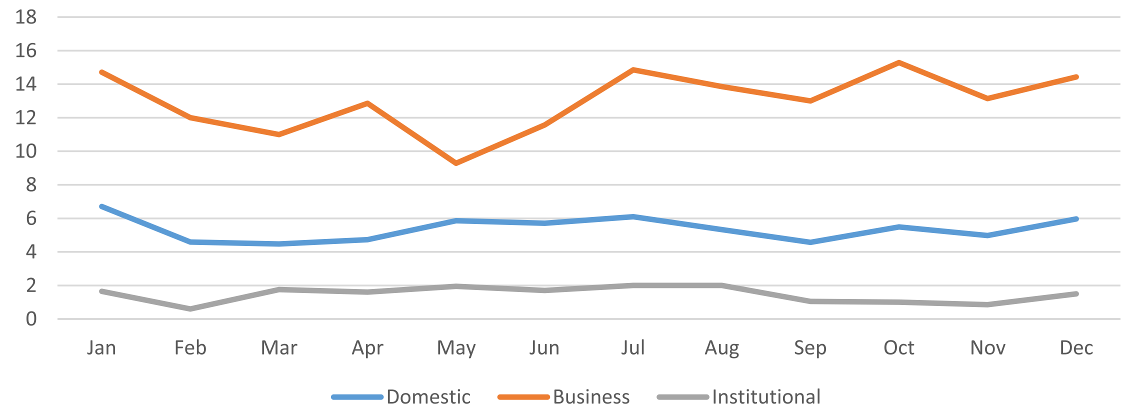


Figure 10. Average monthly demand per customer segment for 2021 (kWh).

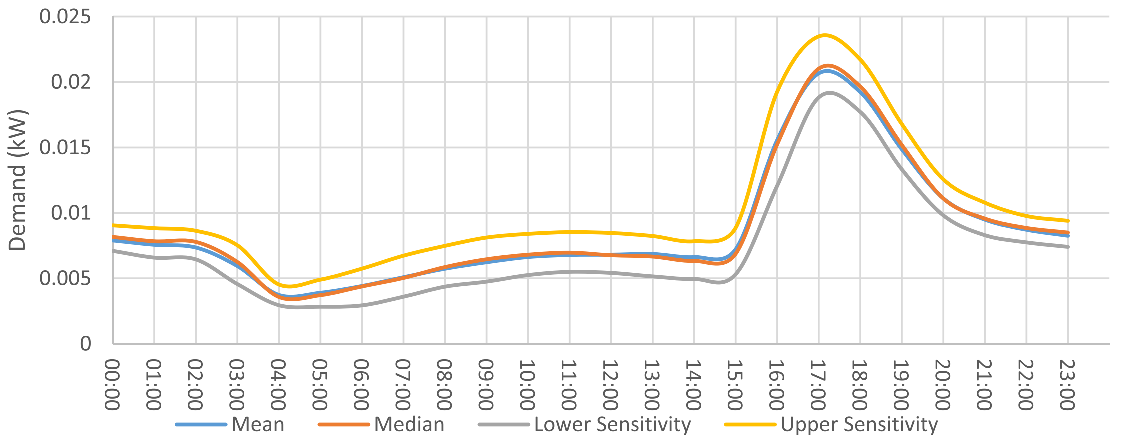


Figure 11. Average load profile for entire minigrid.

with the main economic activities in the village, specifically agricultural processing within rice and maize value chains.

4.2. Economic indicators

4.2.1. Sales revenue

Total monthly minigrid revenue from electricity sales for 2021 is shown in figure 13, revealing a seasonal consumption peaking in July at 516 USD/month and reducing to 180 USD in March. Figure 14 shows ARPU following a similar trend ranging from 3.00 USD/month in March to 8.86 USD/month in July. The mean

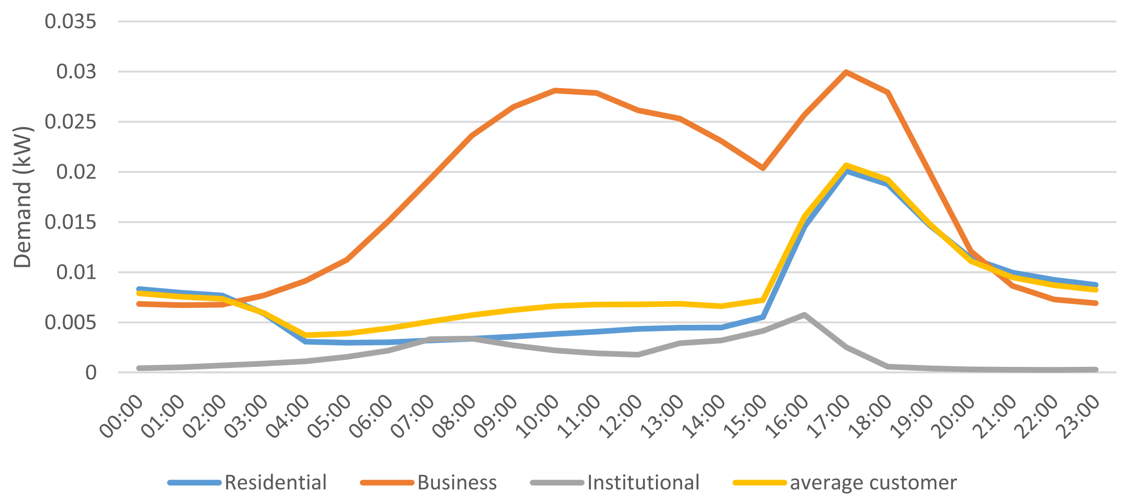


Figure 12. Customer segment mean load profiles.

Table 4. Input Parameters for calculating utilisation factor.

Parameter	Value
Location of the minigrid	−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	4419 kWh
Utilisation factor	21.6%

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) [43]. The data shows a seasonal correlation between minigrid 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), highlighting the importance of increasing revenue through promoting productive uses of energy through business support. Comparison of ARPU with monthly OPEX costs can be used to or 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.

4.2.2. Cost per connection, cost per kW and total cost of power

A summary of CAPEX costs is outlined in table 5 of USD 1700/connection and USD 8869 kW^{-1} are towards the higher end of current benchmark figures, with [43] stating that minigrid CAPEX cost in SSA currently range from 4000 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 minigrid 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.

Site based operational costs for 1 year logged through EASE project records outlined in table 6 show a total of USD 316.4 month on average or USD 3796.8 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 [43]. A comparison with monthly revenue (figure 13) reveals revenue only just covering site-based costs,

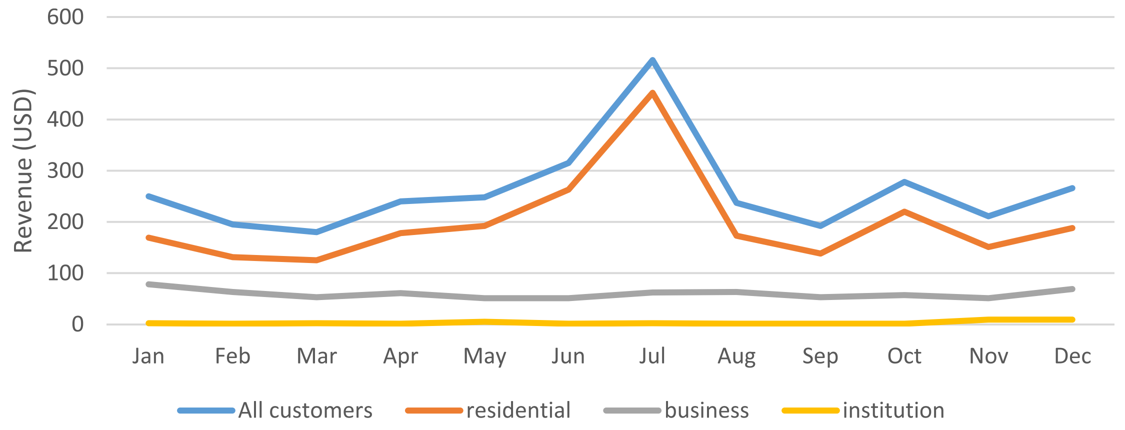


Figure 13. Customer disaggregated total revenue (USD), 2021, Mthembanji.

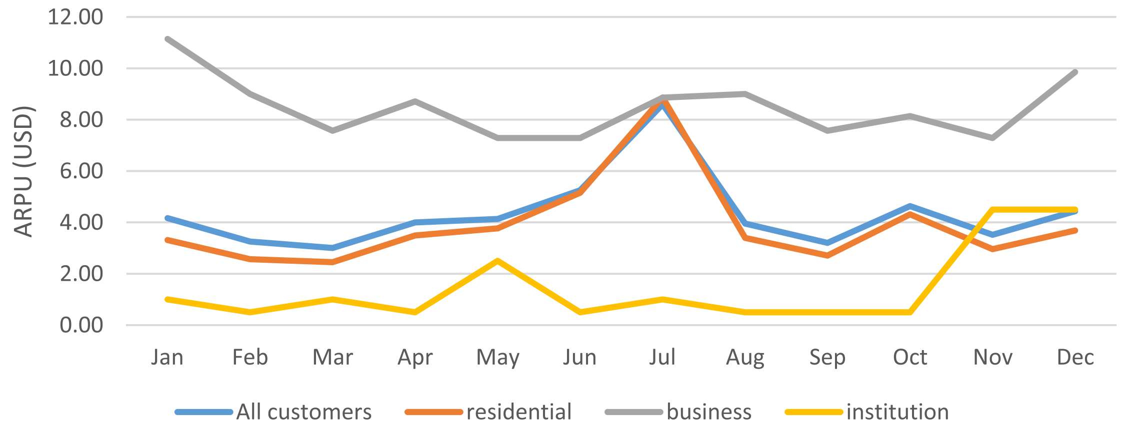


Figure 14. Customer disaggregated average revenue per user per month (USD), 2021, Mthembanji.

Table 5. Minigrid CAPEX summary.

Item	Cost
Generation	$ 55 603
Distribution and smart meters	$ 27 968
Installation and fees	$ 18 425
Total	$ 101 995
Cost per connection	$ 1700
Cost per kW	$ 8869

compromising financial sustainability without interventions on tariffs, demand or operational costs. The total demand of energy sold for 2021 is 6369 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. Minigrid 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.

4.3. Social impact indicators

4.3.1. Demographics and gender equity

Table 7 shows the minigrid serves 335 people, with an average household size of around 6 and a maximum household size of 12 throughout the surveys. The number of female headed houses has remained low at 4. Figure 15 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.

Gender disaggregated education levels as reported in the baseline survey are shown in figure 16, which have not changed in subsequent surveys. The majority of customers have completed primary school (Form

Table 6. OPEX costs.

OPEX component	Month cost (USD)	Annual cost (USD)
Data for 3 G 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 × 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	3796.8
Cost per customer	5.27	63.28

Table 7. Household demographics.

	Baseline	Survey 1	Survey 2
Total people in household	355	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

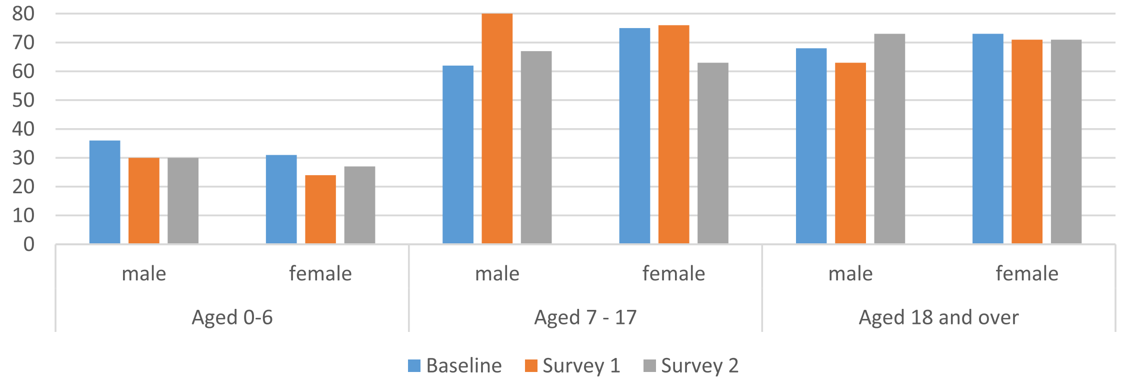


Figure 15. Number of people in houses with a connection disaggregated by gender and age.

1–4), with 24% completing secondary school (Standard 1–8), 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 minigrid 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.

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 17 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 respect within the community and household.

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 minigrid impact in these themes.

4.3.2. 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 18 depicts how energy device use has changed since installation, indicating all non-minigrid devices, including PSP, SHS, 12 V Battery, and dry-cell battery use, have decreased since minigrid 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

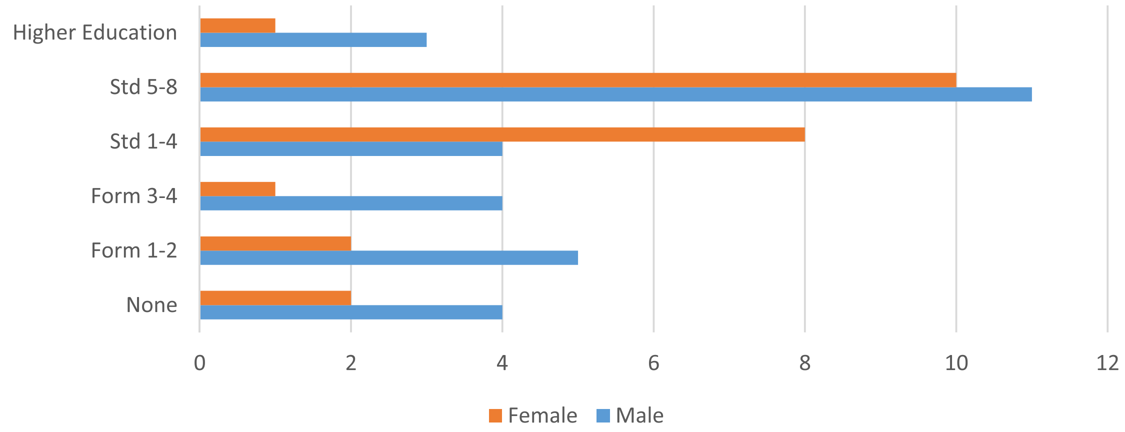


Figure 16. Education level of survey respondent disaggregated by gender (baseline).

have a significantly higher cost/kWh than the minigrid. The evolution of lighting device use since installation is shown in figure 19. As minigrid 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 minigrid lighting is adequate or if additional lighting devices are required. Customers are currently offered four internal and one external lights. Figure 20 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 21 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.

4.3.3. 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 minigrid powers eCook devices. 40% of customers indicated access to health information has 'very much improved' or somewhat improved, shown in figure 22.

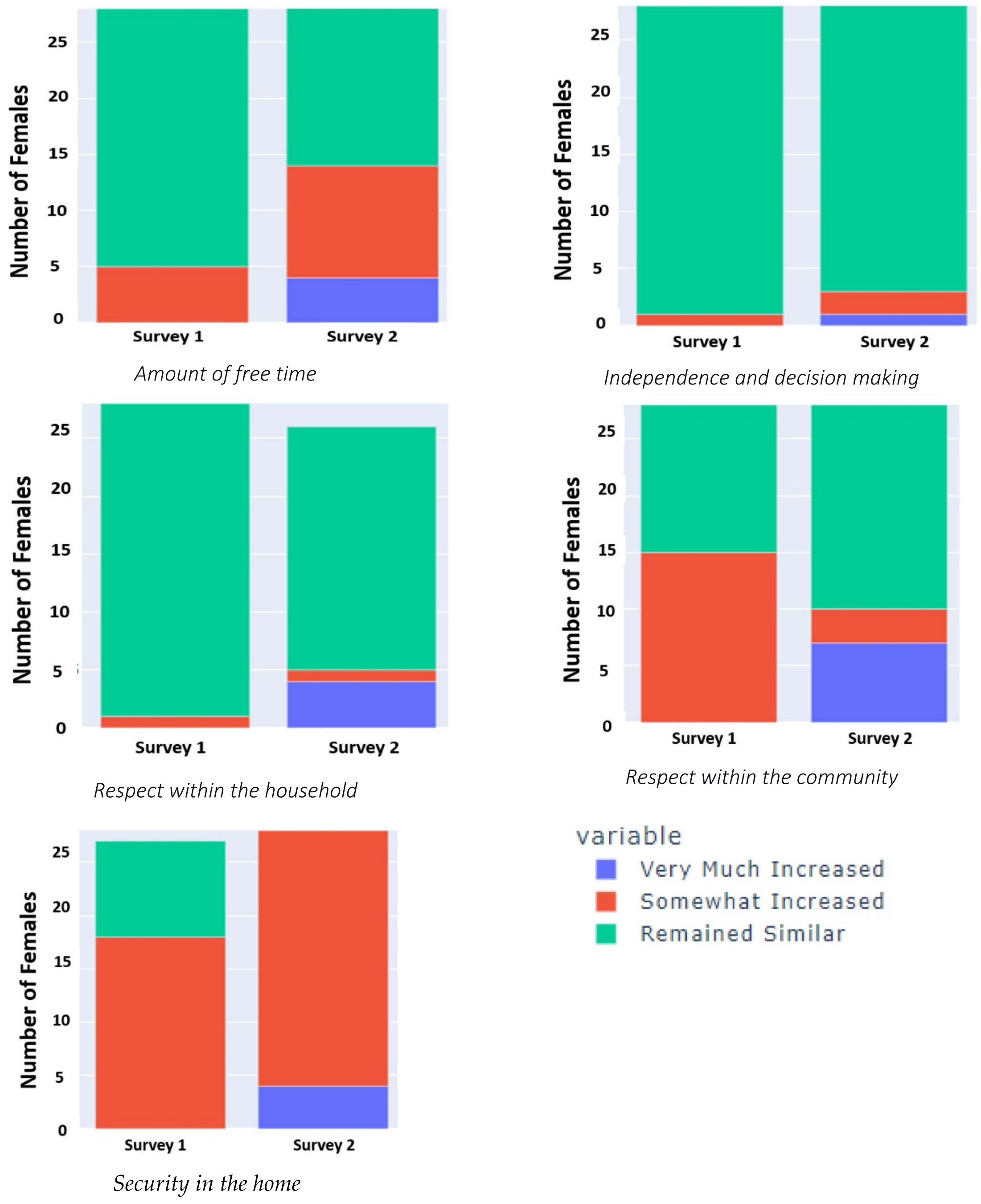
The number of schools connected with access to ICT has remained at 1. The percentage of households reporting that children study at home has reduced from 92% in the baseline to 89% in Survey 1 and 79% in survey two, however study sessions are also conducted at school after dark, and children whose homes are not connected to the minigrid benefit from this arrangement. Figure 23 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 minigrid.

The community's access to local and national news since installation is summarised in figure 24. 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 25 shows the number of mobile phones and smart phones owned by minigrid 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 26, which demonstrates a general trend of increased satisfaction over time. The minigrid provides in-house phone charging for all customers. Tracking phone ownership and satisfaction helps measure the minigrid's impact on increased connectivity. However, to accurately attribute this impact, it is necessary to compare it with a similar unelectrified village experiencing regional trends in phone ownership.

4.3.4. Employment, finance and PUE

Mean monthly income and expenditure is shown in figures 27 and 28. As income is highly volatile, questions ask for estimates of the highest and lowest monthly income and expenditures, although expenditures were



Amount of free time

Independence and decision making

Respect within the household

Respect within the community

Security in the home

Figure 17. Female empowerment KPI tracking.

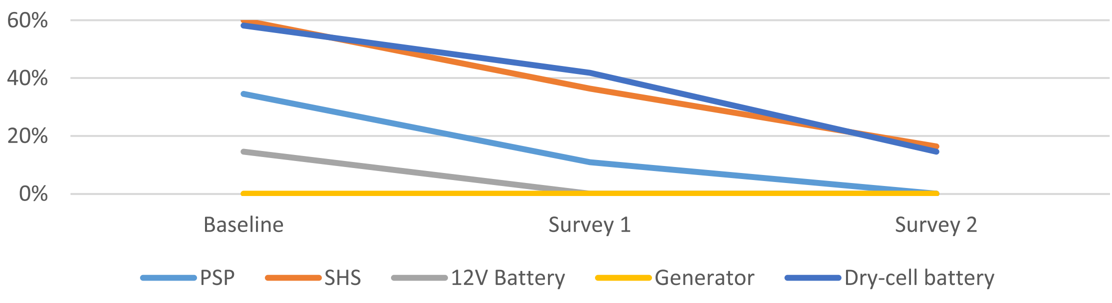


Figure 18. Energy devices.

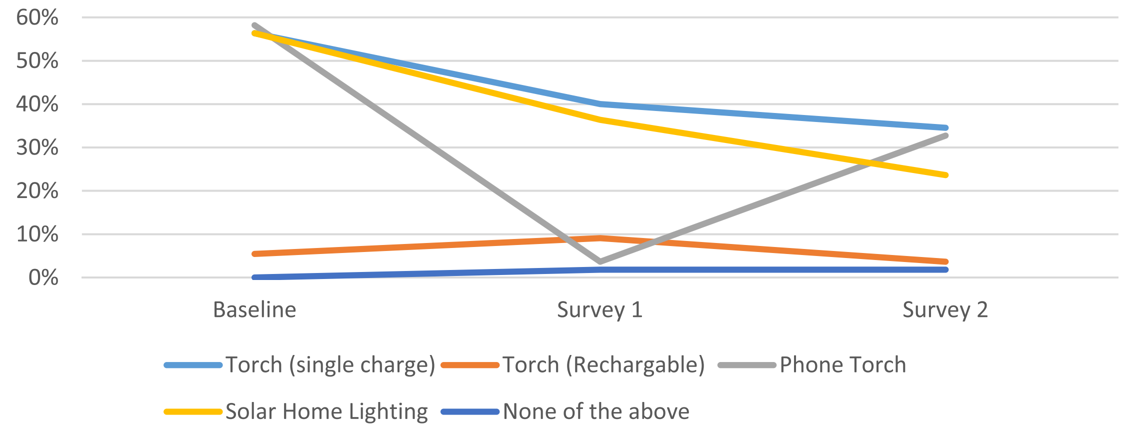


Figure 19. Lighting devices.

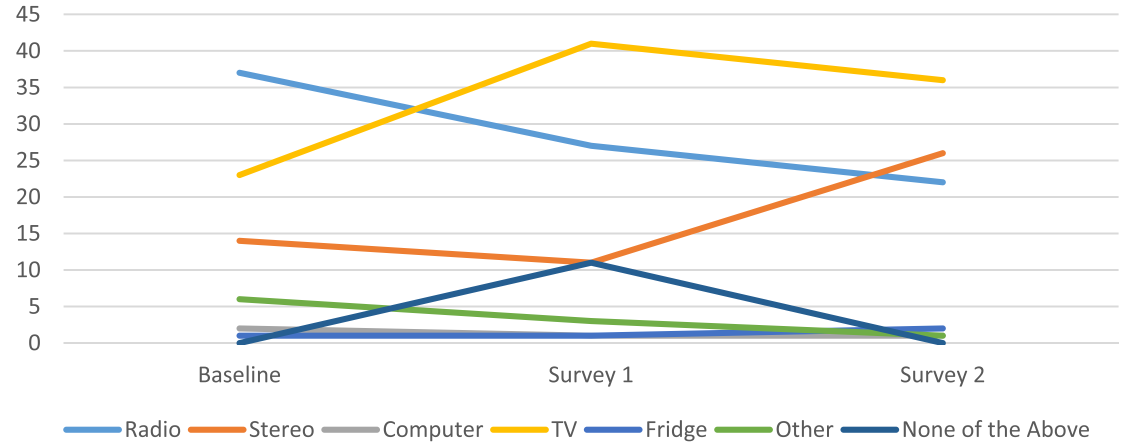


Figure 20. Appliance use.

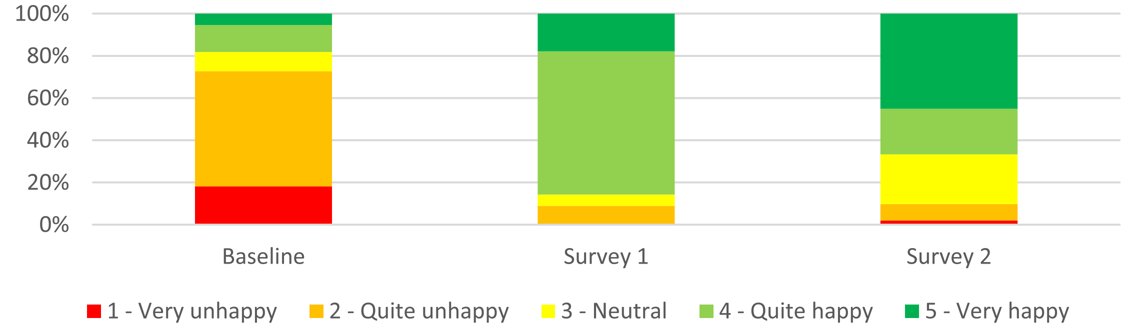


Figure 21. Satisfaction with access to energy.

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 [76] 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 ‘do not know’ for all responses.

Figure 29 shows the number of businesses connected to the minigrid 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

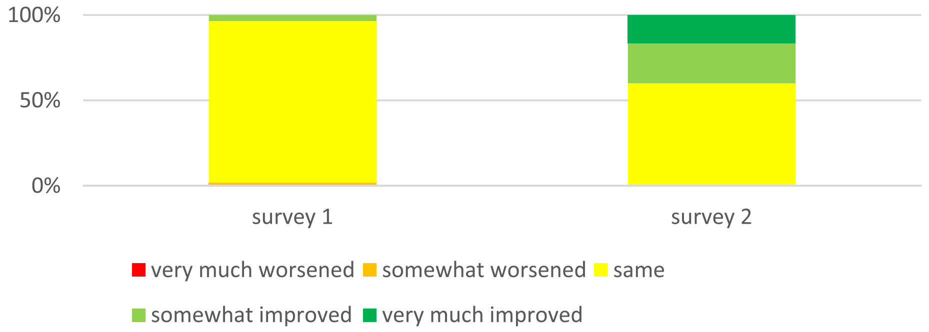


Figure 22. Access to health information.

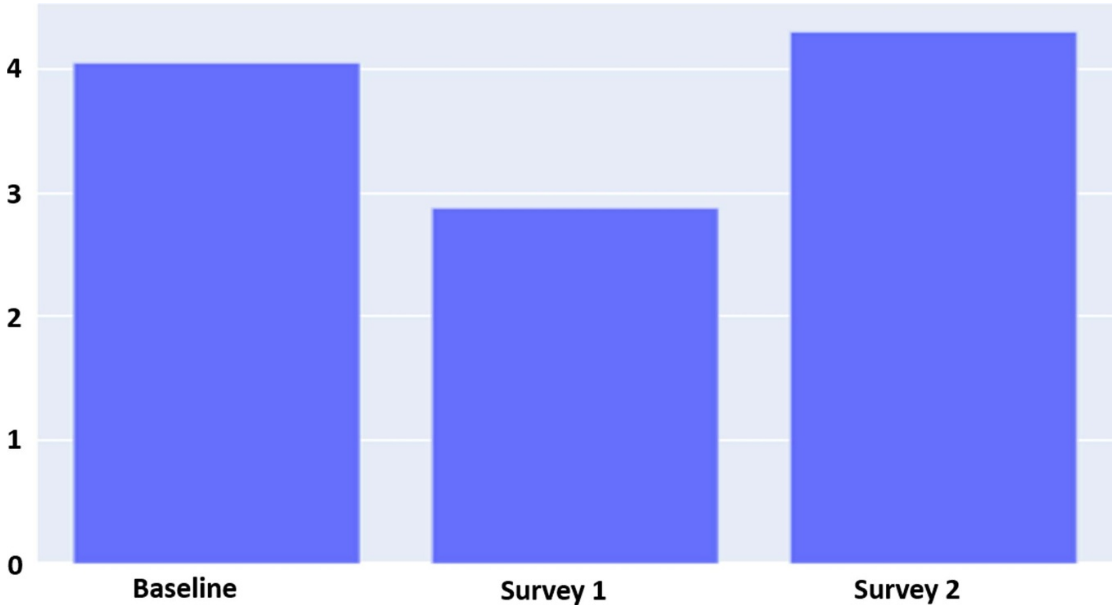


Figure 23. Average number of hours spend studying in the home.

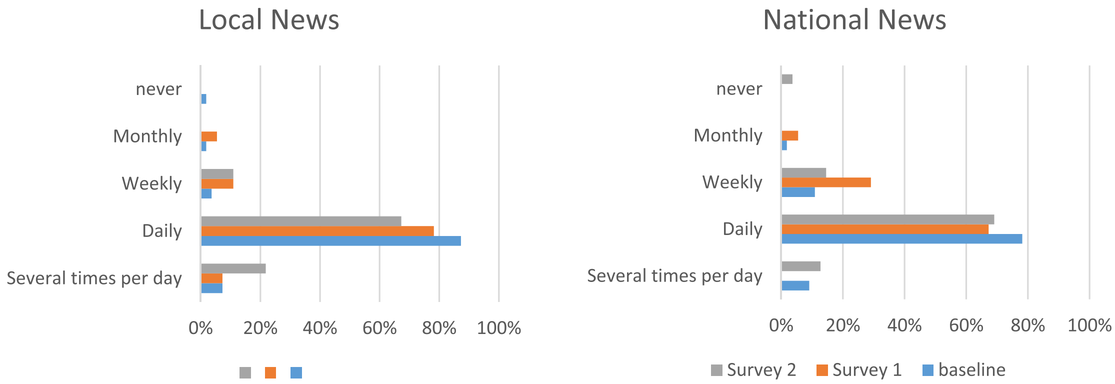


Figure 24. Access to local and international news.

above rise in businesses are all 'household businesses'. Tracking new businesses is essential for predicting load profiles and modelling minigrid future revenue.

Business income and expenditure is shown in figure 30 for business only customers, and figure 31 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

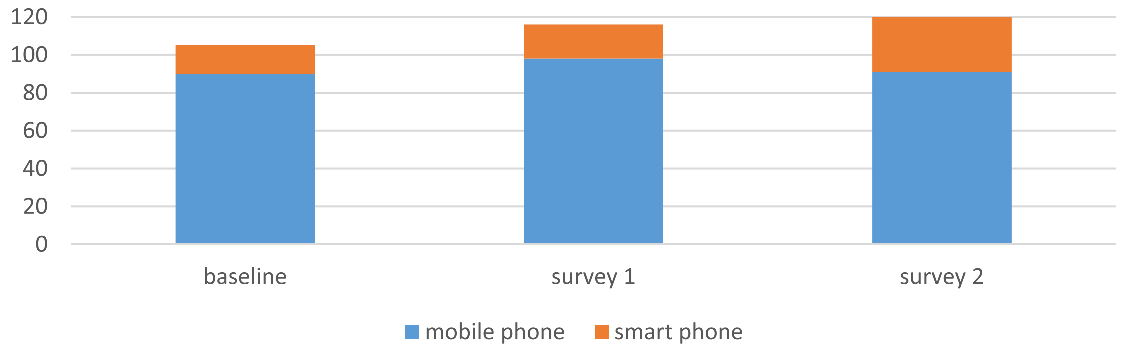


Figure 25. Mobile phone and smart phone ownership.

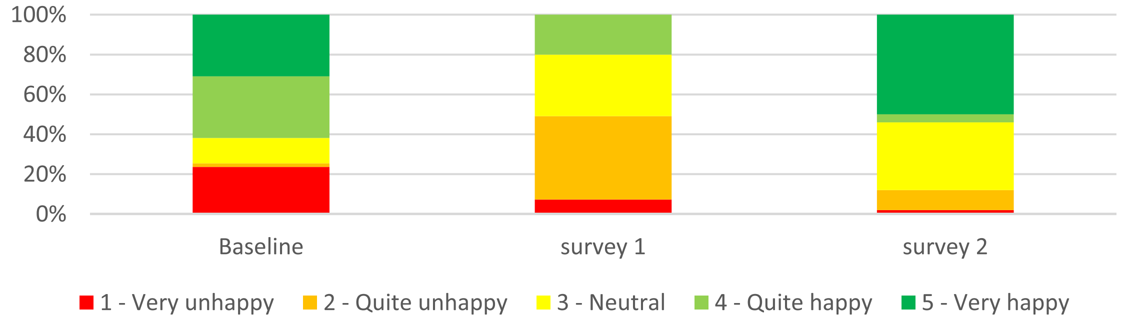


Figure 26. Satisfaction with access to smart phones.

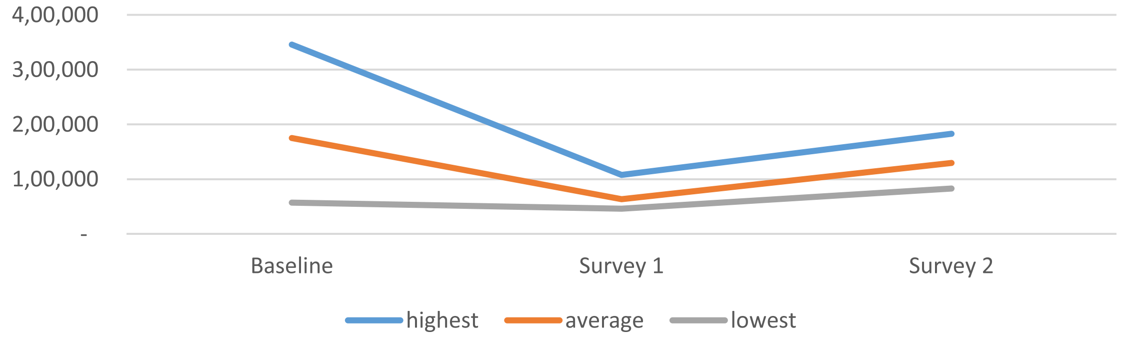


Figure 27. Mean monthly income levels stated by respondents (MWK).

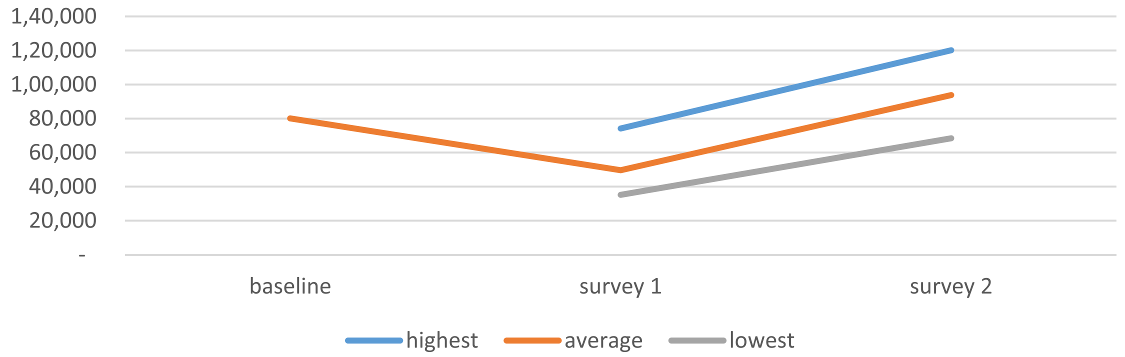


Figure 28. Mean monthly expenditure (MWK).

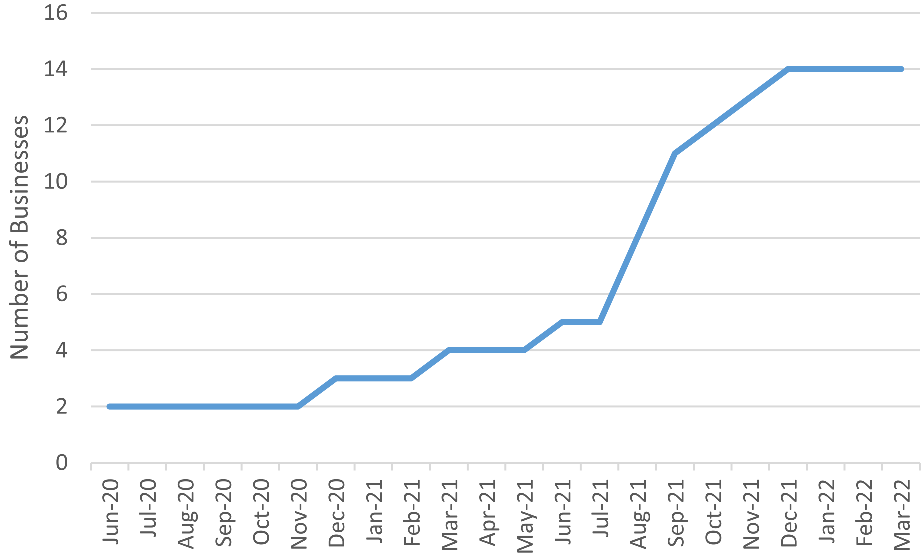


Figure 29. Number of businesses connected.

Figure 30. Business only income and expenditure.

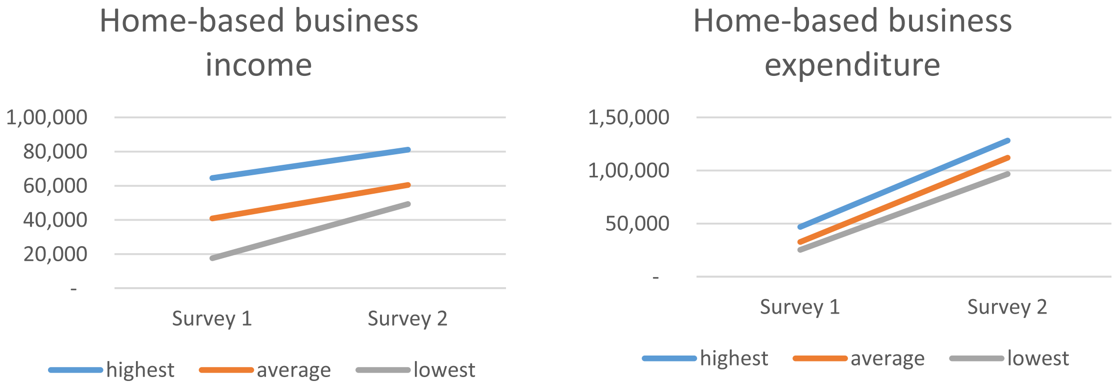


Figure 31. Home based business income and expenditure (MWK).

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.

Perception of financial security corresponds to tariff satisfaction resulting from tariff adjustments made between surveys, as demonstrated in figure 32. 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

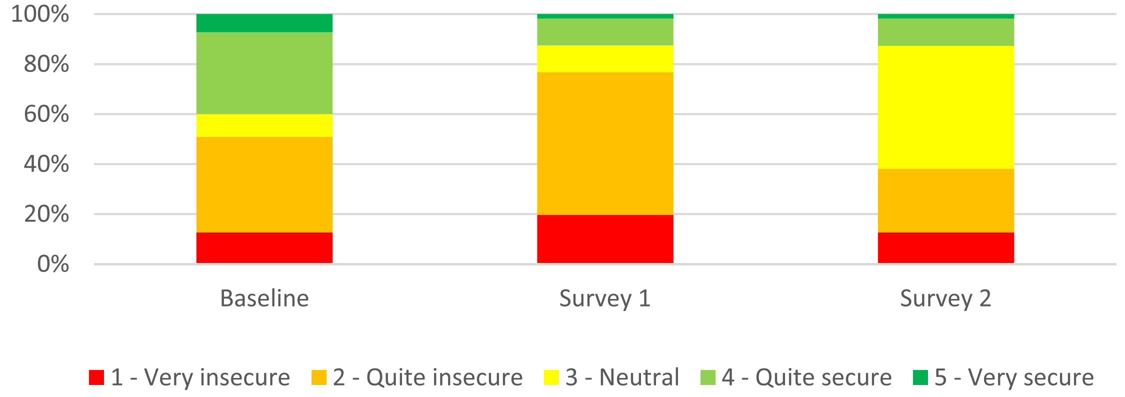


Figure 32. Perception of household financial security.

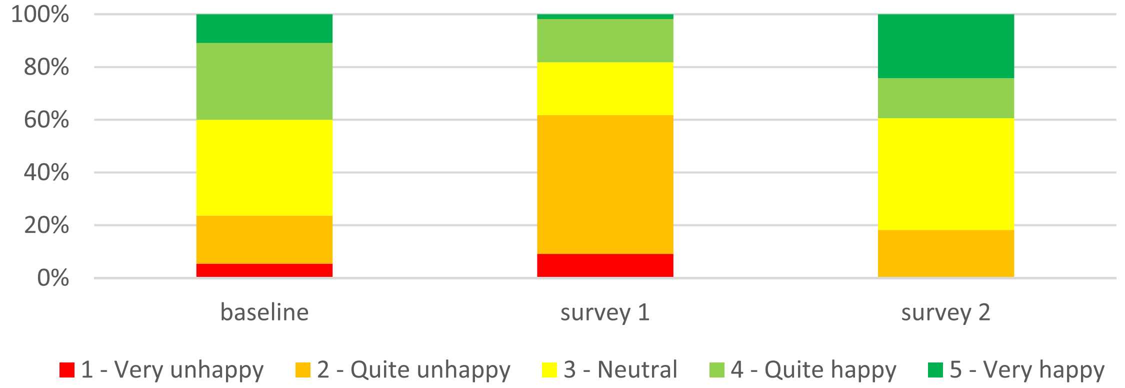


Figure 33. Satisfaction with employment status.

employment status is show in figure 33, showing an increase in 'quite unhappy' and 'very unhappy' responses from baseline to survey 1 (23%–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.

4.3.5. Tariff and service

In terms of financial satisfaction with the minigrid, figure 34 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 (75% day time discount applied) and an associated increase in willingness to pay. Figure 35 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 36, indicating over 50% of customers still regarding the minigrid 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 minigrid complies with the international development ethos of 'do no harm', where it is essential that minigrid developers avoid exacerbating rural poverty, by pushing rural customers deeper into it through a high cost of electricity.

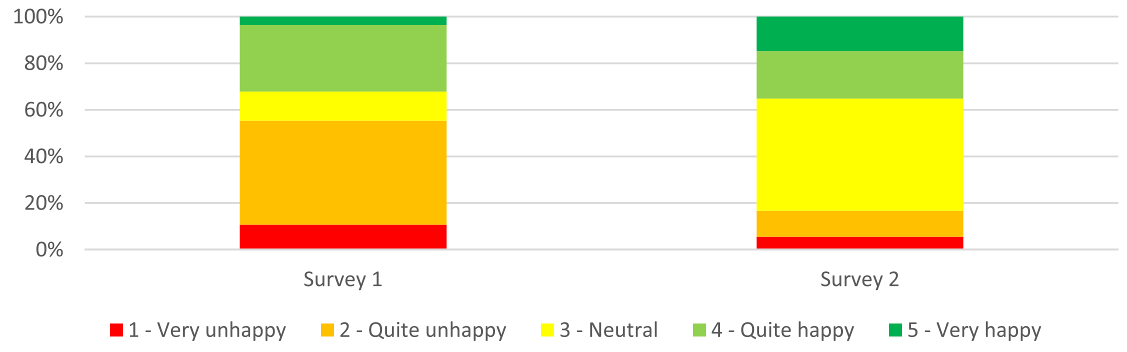


Figure 34. Tariff price satisfaction.

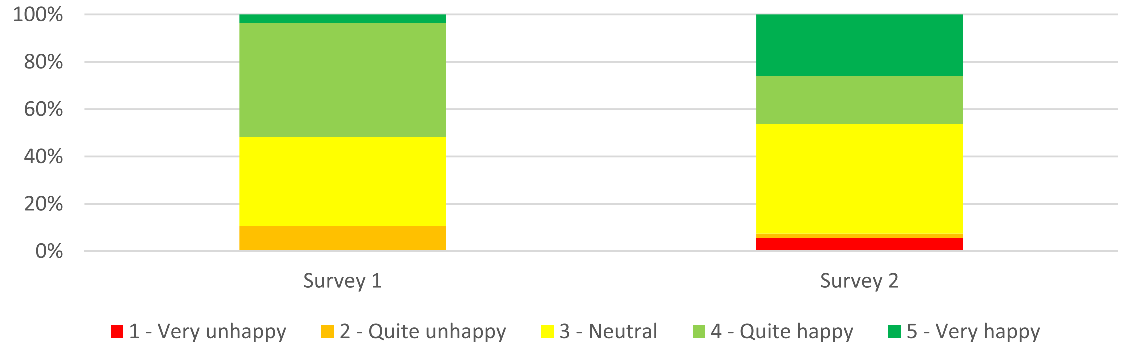


Figure 35. Payment method satisfaction.

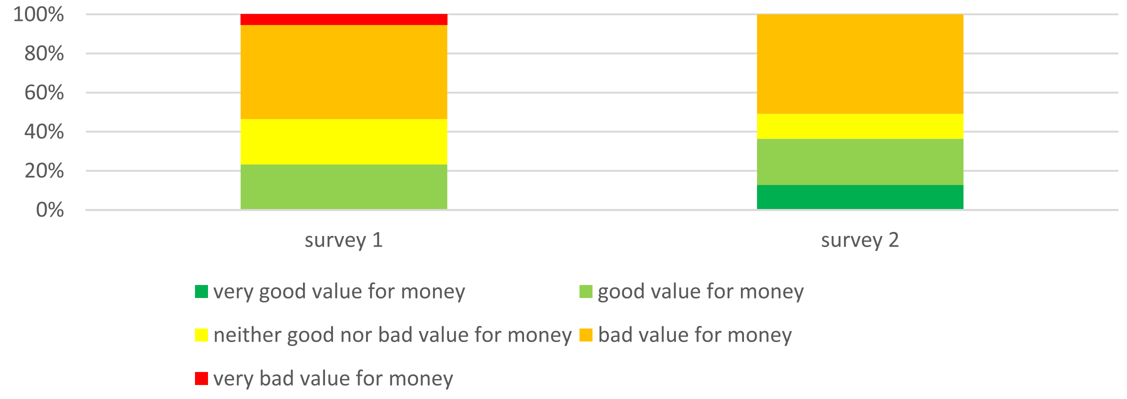


Figure 36. Value for money.

Responses to the 'To what extent has the quality of life of you and your household changed since getting the connection?' (figure 37) shows that by Survey 2, 80% of respondents stated 'very much improved' with a further 29% reported 'somewhat improved'. Figure 38 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 minigrid, 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.

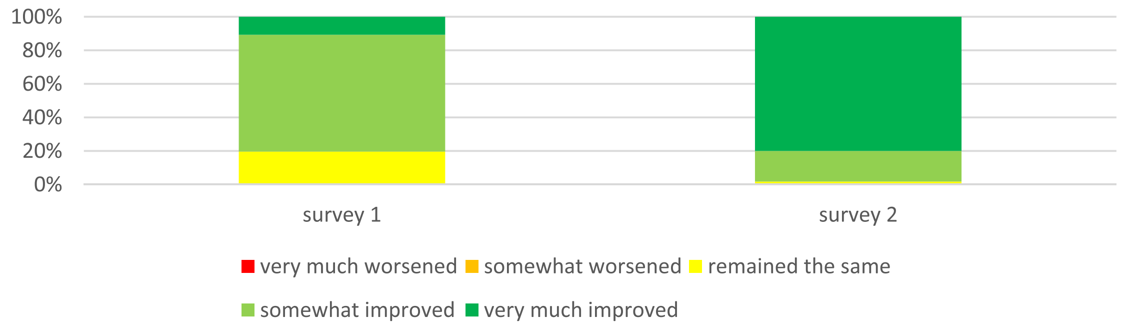


Figure 37. Change in quality of life.

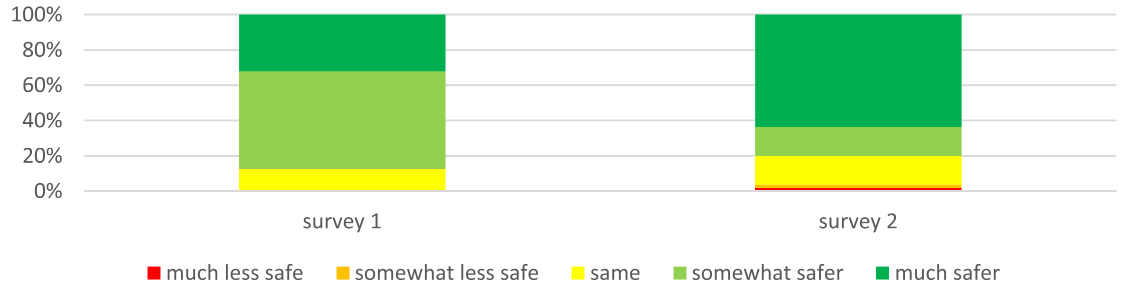


Figure 38. Perception of safety.

5. Discussion and recommendations

5.1. Technical

Real-time data access through remote monitoring and smart meters adds value to the system's operation by informing operation and maintenance procedures, business modeling, and future system design. Remote monitoring of the generation system is essential for troubleshooting, gaining insights into system performance, and providing early warnings of potential issues, positively affecting system sustainability. As minigrid companies scale up, tracking technical KPIs is crucial for robust asset management strategies, reducing lifetime costs, and increasing system availability and output. Building capacity for data analysis and understanding of remote monitoring data is also needed.

At Mthembanji, excessive downtime caused by poor mobile signals reduced smart meter functionality, leading to frequent blackouts and reduced customer satisfaction. This issue highlights the challenges of trialing new technology in remote environments. Training local site agents to reset smart meter cores can mitigate maintenance costs and reduce downtime. Addressing low utilisation rates is another priority. Despite a 75% daytime discount to encourage daytime use, significant barriers remain, such as access and affordability of productive use of energy (PUE) appliances. Overcoming these barriers through appliance financing is necessary to fully utilise excess generation capacity.

Monitoring of battery health has provided valuable insight on the technical performance of the minigrid 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.

Understanding customer segment demand and load profiles is valuable for minigrid operators. Insight into electricity use in previously unconnected communities aids in optimising technical and business designs. Promoting data sharing and further research on load profiles can improve accuracy in predicting customer segment demand [77].

5.2. Economic

The economic indicators in this study are designed to evaluate both the performance of the minigrid system and its contribution to the local economy. ARPU and total revenue provide insights into the financial sustainability of the minigrid by measuring income generation and customer willingness to pay. CAPEX and OPEX assess the cost-efficiency of the system, highlighting areas where cost reductions can be achieved for better economic performance. Additionally, the study examines the impact of the minigrid on local economic activities, such as the establishment of new businesses and increased employment opportunities, which are indicators of the minigrid's contribution to local economic development. By tracking these indicators over time, the study aims to capture both the operational success of the minigrid and its broader economic benefits to the community.

Capital costs for the Mthembanji minigrid were higher than benchmarks in Africa due to the nascent nature of the Malawian minigrid market as well as the relatively small system size. Local unavailability of components and lack of experienced installers increased costs. As the market matures, economies of scale and efficiency savings should reduce costs. Project managers should allow for contingency in budgets and track exchange rates to mitigate financial risks. Policymakers can support this transition by strengthening supply chains and ensuring the availability of foreign capital.

ARPU data provides insight into rural customers' ability and willingness to pay. Initial tariffs were found to be too high, necessitating adjustments. Ongoing assessment of willingness to pay is essential for finding sustainable tariff levels that ensure customer satisfaction and sustainable electricity consumption. Data sharing on ARPU between developers can inform sustainable business models.

OPEX was high, with ARPU only covering site-based costs. High operational costs are linked to the challenges of reaching remote locations and trialing unproven strategies. Reducing these costs through in-house maintenance technicians and efficient logistics strategies is one approach. Increasing revenue through higher demand, either by adding customers or promoting daytime demand, is another strategy. At Mthembanji this is being addressed through implementation of rice milling operations at the site.

Smart subsidies are necessary to enable solar minigrids to scale [77, 78]. Universal subsidies exist for grid-connected electricity in developed countries, and similar support is needed for rural communities in developing regions. Data sharing on costs and income from multiple projects can build a case for government subsidies based on quantifiable needs.

5.3. Social impact

Tracking social impact reveals how minigrids contribute to achieving multiple SDGs and provides a more comprehensive view of performance than just technical and economic metrics. Financial sustainability relies on customer satisfaction and demonstrated social impact to attract investors and donors.

Understanding household profiles helps tailor community engagement efforts and predict energy use. Comparing demographic data across sites can inform revenue predictions and energy use patterns. Energy access metrics contribute to national SDG7 targets and inform business models through understanding demand. Positive impacts on health, education, and communication were observed, but direct attribution requires more robust social science research. Continued community engagement is essential for project success, from pre-installation to regular engagement throughout the project cycle. Safety training is also crucial to prevent injuries.

Increases in the number of businesses indicate local economic development. However, attributing financial impacts to the minigrid is complex due to other influencing factors. Understanding income and expenditure trends helps assess positive economic impacts and inform business strategies.

Female empowerment indicators show generally positive trends. Detailed interviews and focus group discussions are needed to fully understand the impact on women. Tracking gender impacts is necessary for social impact investors and energy service social enterprises.

Customer satisfaction with pricing reveals high dissatisfaction with electricity costs. Affordability is a key aspect of SDG7, and finding tariffs that foster demand without increasing poverty is essential. Future research can investigate the impact of tariff reductions on utilisation rate and associated revenues. Tracking socio-economic impacts of minigrids requires investment in community support and engagement resources, including PUE training, appliance financing, health and safety, and gender-focused initiatives.

When evaluating the social benefits of solar minigrids, it is crucial to distinguish between the global framework of the SDGs and the localized perspective of the benefiting communities. The SDGs offer universal metrics for progress in areas such as poverty, health, education, gender equality, and clean energy, facilitating the comparison of outcomes across different regions. In contrast, the community perspective focuses on tangible impacts experienced by individuals and households, prioritizing context-specific metrics like local economic development, health improvements, and social cohesion. Integrating both perspectives is essential for a comprehensive evaluation. This involves aligning community-specific metrics with broader

SDG indicators, ensuring local impacts contribute to global goals. Effective community engagement in developing KPIs ensures they are meaningful to those directly affected. Combining standardized and locally relevant indicators provides a full picture of social benefits, while continuous feedback allows for the adaptation and refinement of projects over time. This balanced approach ensures the evaluation of social benefits is both globally relevant and locally meaningful, capturing the full impact of solar minigrids.

Indicators alone do not prevent unintended consequences of development, but they are crucial for identifying and mitigating them. They provide a structured way to monitor and evaluate impacts, allowing practitioners to track progress and identify potential issues early. Using comprehensive indicators that include technical, economic, and social metrics helps gain a holistic understanding of a project's impacts and take corrective actions when necessary. However, indicators must be well-designed, context-specific, and regularly updated. They should be developed with input from all stakeholders, including affected communities, to capture the full range of potential impacts. Continuous monitoring and feedback loops are essential for promptly addressing negative consequences. Indicators should be complemented by robust planning, community engagement, adaptive management, and ongoing evaluation. This integrated approach ensures development projects achieve their goals while minimizing and managing unintended consequences.

5.4. Limitations and future work

The small sample size of 60 impacts the validity and generalisability of the findings by reducing the statistical power and increasing the likelihood of missing significant effects. It limits the ability to generalise results to larger populations, as the specific characteristics of the sampled community may not be representative of others. Additionally, small samples are more prone to the influence of outliers and random variation, which can skew results and obscure true trends. Therefore, while the findings offer valuable insights into the impact of the minigrid on this community, caution is needed when extrapolating these results to broader contexts. Future research should include larger and more diverse samples to enhance the robustness and generalisability of the findings.

The study reports changes observed within approximately 18 months of the electrification intervention, but it is important to acknowledge that the full impact of such projects often takes many years to manifest. To capture the long-term effects and trends, it is essential to continue monitoring the project with follow-up surveys. This extended observation period will allow for a more comprehensive assessment of the energy generation capacity of the PV system, the evaluation of the health clinic's impact once it is connected, and the assessment of the economic and social benefits of the rice milling system2. Continued monitoring will provide a deeper understanding of the sustainability and effectiveness of the minigrid, ensuring that the initial trends identified are sustained and that any long-term impacts are accurately documented and analysed.

To strengthen the causal inference in this and similar studies, it will be valuable to clearly define counterfactuals and distinguish the impact of the minigrid from other general improvements occurring in the village. Currently, it is challenging to attribute specific outcomes, such as increased phone ownership and connectivity, directly to the minigrid, given the broader regional trends in technology adoption. To address this issue, future research coul include a comparable unelectrified village as a control group. This approach will help isolate the effects of the minigrid by providing a baseline against which changes in the electrified village can be measured. By comparing indicators such as phone ownership, economic activities, and health outcomes between the electrified and unelectrified villages, the study can more accurately attribute observed changes to the minigrid intervention. Implementing this methodology will improve the robustness of the findings and provide clearer evidence of the minigrid's specific impacts on the community.

6. Conclusions

This paper introduces a novel KPI framework designed to holistically evaluate the sustainability and impact of solar minigrids. By incorporating technical, economic, and social metrics, the framework provides comprehensive insights into minigrid performance, which are essential for improving system design, business models, and community engagement strategies.

The case study of the Mthembanji minigrid in Malawi demonstrated the value of this holistic approach. Key findings revealed significant downtime caused by smart meters, seasonal revenue variations that cover site-based costs, and positive social impacts on community well-being. These insights highlight the necessity of real-time data access through remote monitoring and smart meters, which enhances system operation by enabling timely maintenance and operational adjustments.

The key takeaway from this research is that a holistic evaluation framework is critical for understanding and optimizing the full range of impacts of solar minigrids. Practitioners, policymakers, and investors should adopt and adapt comprehensive KPI frameworks to ensure that minigrid projects not only meet technical and economic goals but also deliver meaningful social benefits to the communities they serve. Practitioners should implement these frameworks in all phases of minigrid projects and engage with local communities to tailor the indicators to specific needs and contexts. Policymakers need to develop policies that encourage the use of such frameworks and support data sharing among minigrid operators to foster best practices and continuous improvement. Investors should prioritise funding for projects that demonstrate a commitment to holistic evaluation and sustainability, ensuring that social impacts are considered alongside technical and economic performance.

By integrating these practices, stakeholders can enhance the effectiveness and sustainability of solar minigrid projects, ultimately contributing to broader goals of poverty reduction and sustainable development.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: malawi-microgrids.herokuapp.com.

Conflict of interest

The authors declare that they have no competing interests. The research was approved by the University of Strathclyde Ethics committee and consent was obtained for all surveys carried out with community members.

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Appendix. Case study KPIs

Table 8. Tracked technical and economic KPIs.

Indicator	Units	Data collection
Daily communication uptime	Days	Steamaco
Number and length of power outages	#, days	Steamaco
Monthly electricity production	kWh/month	Sunnyportal
Annual electricity production	kWh/year	Sunnyportal
Battery state-of-charge—daily, weekly, monthly	%	Sunnyportal
Battery temperature daily	°C	Bespoke logger
Customer segment monthly total and average consumption	kWh per month, load profiles	SteamaCo
Utilisation factor	%	Sunnyportal
Total energy sales revenue	USD/month	Steamaco
Average monthly revenue per user	USD/month	Steamaco
Customer segment revenue	USD/month	Steamaco
Cost per connection	USD/connection	Project Documentation
Cost per kW installed	USD/kW	Project Documentation
Total cost of power	USD/kWh	Project Documentation

Table 9. Tracked social impact KPIs.

KPI	Unit
Demographics	
Number of people in household, gender disaggregated	#,
Female headed households	#
Occupation (formal and informal)	List, description
Education level	% at each level
Energy access	
Number of customers	#
Potential unconnected customers	#
Percentage of the community connected	%
Energy devices used	#
Lighting devices used	#
Household use of other fuels for lighting	Percentage use of other fuels for lighting
Energy access satisfaction	1–5 likert
Health education and communication	
Number of health centres connected	#
Number of burns or injuries related to cooking, lighting or heating	#
Access to health information	1–5 likert
Number of schools connected	#
Number of schools with access to ICT	#
Number of children going to school	#
Number of children studying at home	#
Average hours per night spent by children studying due to electricity access	hours
Increase in access to local news	1–5 likert
Increase in access to international news	1–5 likert
Access to mobile and smart phones	#
Satisfaction with access to phones	1–5 likert
Employment, finance and PUE	
Average, highest and lowest household income	$/month
Average, highest and lowest household expenditure	$/month
Number of businesses and industries connected	, #, list and description of types
Average business expenditure	$/month
Average Business income	$/month
Perception of household financial security	1–5 likert
Customer satisfaction of employment status	1–5 likert
Femal empowerment	
Number of women with access to electricity	#, %
Number of female owned businesses	#
Female perception of electricity impact on: • Amount of free time • Independence and decision-making power • Respect within the household • Respect within the community • Security in the home	1–5 likert
Tariff and Service	
Satisfaction with cost of electricity	1–5 likert
Satisfaction with payment method	1–5 likert
Electricity spend comparison	Average (Ideal spend—current spend)
Perception of value for money	1–5 likert
Perception of payments being a burden	1–5 likert
Perception of change in quality of life	1–5 likert
Perception of increase in safety due to minigrid	1–5 likert
Perception of negative consequences of minigrid	% and description

ORCID iD

Aran Eales https://orcid.org/0000-0001-9090-529X

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