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The Quest for Resilient Sustainable Development and Low-Carbon Energy Transitions: Investigating the Challenges and Success Factors for Mini-Grids in Malawi

Vincent Mwale [1], Richard Blanchard [2,*], Tiyamike Ngonda [3], Richard Nkhoma [4], Chukwudi Ogunna [5] and Long Seng To [5]

1 Energy Systems Department, Mzuzu University, Mzuzu Private Bag 201, Malawi
2 Centre for Renewable Energy Systems Technology, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, UK
3 Department of Mechanical and Mechatronic Engineering, Cape Peninsula University of Technology, Bellville 7535, South Africa; ngondat@cput.ac.za
4 Department of Engineering, Malawi University of Science and Technology, Limbe P.O. Box 5196, Malawi; rnkhoma@must.ac.mw
5 Centre for Sustainable Transitions: Energy Environment and Resilience (STEER), Geography and Environment, School of Social Sciences and Humanities, Loughborough University, Leicestershire LE11 3TU, UK; c.ogunna@lboro.ac.uk (C.O.); l.to@lboro.ac.uk (L.S.T.)
* Correspondence: r.e.blanchard@lboro.ac.uk

Abstract: Renewable energy mini-grids are considered a cost-effective way to provide electricity for a large proportion of the population in developing countries who do not have access to it. Compared with standalone home systems and national grid systems, mini-grids can potentially offer a better service. They can be deployed faster, making them essential for sustainable development, especially in rural and semi-urban areas of developing countries. However, mini-grids often face challenges regarding their resilience, and many fail to survive beyond their pilot phases. This paper aims to identify the factors contributing to the success of mini-grids and to identify common themes that can help existing and future mini-grid developments become more resilient and influence policy decision making. To achieve this goal, we developed a database of the status of mini-grids in Malawi, with the energy generation resource(s) of their installed capacity, enabling factors, and challenges. We undertook a more detailed investigation of two hydro mini-grid systems—Bondo and Chipopoma. We collected qualitative and quantitative data through literature reviews, site visits, interviews, and observations. The study identified 19 mini-grids with a combined installed capacity of 26 MW. Of these, seven had been abandoned, and one was under development. Several factors that affect successful mini-grid efficacy in Malawi were identified, including financial resourcefulness, technical resourcefulness, policies and regulations, community engagement and capacity building, cross-sector linkages, and institutional organisational frameworks. These factors need to be integrated into decision making by all stakeholders to ensure the enhancement of resilience and the sustainable development of mini-grids.

Keywords: mini-grids; energy transitions; resilience; renewable energy; hydropower

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1. Introduction

Malawi has one of the lowest levels of electricity access in the world, with only 14.2% of the population having access in 2021 [1]. This challenge is further exacerbated by the fact that population growth surpasses the annual growth of electricity access; hence, the number of people without access is increasing [2]. It is challenging for countries to achieve sustainable development and energy transitions in such a situation.

A lack of access to electricity and continued dependence on biomass for fuel have subjected the vast majority of people in Malawi and the rest of Sub-Saharan Africa to a life of abject poverty [3–6]. Furthermore, the heightened pressure on natural resources has impeded economic development and people's ability to create sustainable livelihoods. This, in turn, has led to the degradation of the ecosystem. Climate change presents more frequent and severe challenges, particularly impacting poor communities that have fewer options to adapt. These adverse impacts pose a significant threat to achieving the objectives of the UN Agenda 2030 and the AU Agenda 2063.

The disparity in electricity access rates between urban and rural areas is significant. In Malawi, for instance, while urban areas have a 42% access rate, rural areas have only 4% [7]. One of the reasons for this disparity is that utilities in developing countries are hindered by a lack of sufficient generation capacity, poor transmission and distribution infrastructure, high supply costs to remote areas, the inability of low-income households to pay high connection charges, and the weak financial state of utilities [6]. Kende-Robb et al. (2015) observed that the utilities of most governments in Africa are used as vehicles for rewarding the ruling clique through corruption [8]. Grid extension has been used as a political campaign tool as policymakers tend to prioritise the extension of the grid to peri-urban areas to maximise their political support or provide electricity to urban populations that are more politically active and organised compared to the rural populations [9]. It has been observed that areas that can be economically served by grid extension are slowly being exhausted [2].

According to IEA et al. (2020), in recent years, expanded off-grid solutions have improved electricity access rates in many countries [10]. These solutions include decentralised energy systems, such as mini-grids and solar home systems (SHSs). They can work as standalone solutions or complement grid extension efforts to accelerate access to electricity. Mini-grids are 'electric power generation and distribution systems' that 'can either be fully isolated from the main grid or connected to it, but they are also able to intentionally isolate themselves from the grid' [11]. Mini-grids can be powered by conventional or renewable forms of generation. In this paper, we only focus on renewable sources. Whilst there seems to be no consensus on the generation capacity of these systems, it has been stated that mini-grids involve electricity generation in the order of 10 kW to 10 MW [12] or simply any system less than 10 MW [11]. In addition, according to Etongo & Naidu (2022), any system with less than 10 kW or a customer base of 20–100 should be regarded as a micro mini-grid [12]. Irrespective of these definitions, mini-grids could have a significant role in expanding electricity success and increasing their overall installed capacity in a country lacking universal electricity access. But mini-grids need to be designed to ensure they meet end-user requirements or different loads, use the most appropriate (financially and technically) generation, have storage and control equipment, can recover revenues, are operated and maintained effectively and have the potential to grow with future demand. For the thousands of mini-grids that have been built, they are typically bespoke to specific circumstances with different goals of what is to be achieved rather than providing off-the-shelf solutions and making comparisons difficult with all the different permutations. This creates issues in increasing electricity access due to a wide range of organisations being involved, often lacking strategic planning.

1.1. Efforts on Increasing Electricity Access in Malawi

Malawi has implemented several decentralised energy projects to expand access to electricity, including the Ndawala and Malawi Electricity Access Project (MEAP) [13]. Ndawala was initiated after observing that even with electricity grid expansion in rural areas through the Malawi Rural Electrification Programme (MAREP), very few households can afford connection fees and internal wiring costs [14]. MAREP is a division within the Ministry of Energy's Department of Energy, which aims to promote rural electrification. MAREP is funded through levies on energy sales, such as electricity and petroleum products. This project provides wiring services and connections to targeted households by offering each household a soft loan of MWK 55,000 (approximately USD 54). However, before benefiting from the initiative, households must pay a commitment fee of MWK 5000 (about USD 4.90). The loan is repaid through 40% deductions from every unit of electricity the household purchases. Unfortunately, the project supported only 12,982 households across the country [14]. It requires scale-up if it is to make a significant impact on energy access in the country.

The Electricity Supply Corporation of Malawi (ESCOM) implemented MEAP with technical and financial support from the World Bank [15,16]. The aim of MEAP was the "elimination of connection barriers due to unaffordable internal wiring costs providing ready boards to low-income households that cannot afford internal wiring costs". The project targeted support for 280,000 out of 1 million households living within 500 m of existing transformers with electricity connections planned by 2024. The beneficiary households were required to pay a standard connection charge of MWK 25,000 (USD 24) representing 31 percent of the total connection cost of MWK 79,000 (Approx. USD 78). This balance has to be repaid through tariff deductions from each electricity unit purchased by the household [14,17].

Ramping up Ndawala and MEAP has the potential to expand electricity coverage up to about 70–80% of the 1 million targeted households living within 500 m, or 1.5 million households living within 1 km of existing transformers. Expanding these two initiatives was estimated to increase overall national electricity access to around 38% [17] from the current 11.2%. Nonetheless, unless accompanied by tangible and committed initiatives that support the delivery of electricity, the potential developmental benefits of electrification and its ability to alleviate poverty remain unattainable and lack meaningful impact. Moreover, with no increase in generation capacity by the national electricity generation company, expanding these two projects t helps reduce the number of blackouts and alleviates the strain on the current electricity system. These two projects were for grid extension and did not consider the population that could economically be served with mini-grids. Mini-grids have the potential of economically providing access to an estimated 40% of those without electricity access in Sub-Saharan Africa and contribute towards universal electricity access by 2030 [18].

1.2. Energy Transition and Sustainable Development

IEA (2021) reported that energy accounted for around 75% of global greenhouse emissions in 2019, while the consumption of fuels for electricity and heat generation contributed 41% of global CO_2 emissions in 2021 [19]. Addressing climate change and meeting the net-zero carbon emissions target by 2050 requires a paradigmatic shift towards low-carbon energy transitions [20]. This energy transition has been defined as an increase in the volume and proportion of renewable energy replacing traditional or fossil fuels [21,22]

Expanding access to modern energy is a precondition for the alleviation of poverty and increasing shared prosperity for modern living [6,23,24]. Access to modern energy has direct linkages with the wider development agenda. A review of all the 169 Sustainable Development Goal targets indicates that energy is interconnected with 125 targets, which is 74% of all targets [6]. Expanding electricity access can play an important role in raising per capita income, creating jobs and impacting positively in areas of health, education, livelihoods, and food security [22,25]. The African Union (AU) Agenda 2063 is of the same proposition that access to modern energy impacts other goals, such as enhancing economies and job creation and environmentally sustainable climate resilient economies and communities [26]. Indeed, several studies in different countries, including Rwanda, Bangladesh, South Africa and Cambodia, have established positive correlations between household incomes, health, education, food security, poverty reduction, gender equality, improved livelihoods, and energy access [27–29].

1.3. Success Factors for Renewable Energy Implementation

Renewable energy planning is a complex process that involves considering numerous factors. The success of a project depends on its completion within a given scope and budget while ensuring that the desired quality is delivered to customers. To increase the chances of success, it is essential to identify the enabling factors. This can be achieved by analysing prior studies that cover established, ongoing, and planned renewable energy projects. The analysis, which uses case studies, recognises the diverse considerations necessary to account for the different scales and sophistication of technologies under review.

A guide for the critical success factors necessary to successfully implement renewable energy projects was set out by [30]. The factors highlighted were classified into six categories based on their specific features. These categories cover the social, organisational, managerial, economic, environmental, technological, and governance dimensions. Critical success factors similarly aggregated through the survey of existing renewable energy projects in China show that success factors related to project planning, cooperation, contractors and supplies and the project atmosphere are inextricably intertwined with the success of future projects [31]. These factors must be incorporated into planning to support efficient capital circulation and determine the overall outcome.

There have been limited published studies in the literature on the use of energy by communities and how mini-grids contribute to local economies [9]. Therefore, it is appropriate to gather information about mini-grid experiences and make it available to relevant stakeholders [32]. This paper aims to identify the factors that lead to the success or failure of mini-grids by analysing past experiences and identifying common themes. To achieve this, we developed and analysed a database comprising all renewable energy mini-grids in Malawi and examined two case study hydro mini-grids—Bondo and Chipopoma. Qualitative and quantitative data were collected through the literature review, site visits, interviews, and observations.

This study aims to fill the research gap by identifying key factors contributing to the resilience and success of mini-grids in Malawi. Specifically, it seeks to answer the following questions:

a. What are the enabling factors for successful mini-grids?
b. What challenges to sustainability do mini-grids face?
c. How can these challenges be mitigated to enhance the resilience of mini-grids?

Understanding this is crucial for Malawi and other developing countries as it enhances the resilience and sustainability of mini-grids, thereby offering a viable pathway to expand electricity access and foster sustainable development.

2. Methodology

This study used a mixed methods approach that included the following:

a. Surveying mini-grid systems in Malawi.

The survey was designed to create a comprehensive database of Malawi's mini-grid systems, whether planned, abandoned, or active. This was accomplished through a literature review and interviews with industry experts. The collected data included information on installed capacities, locations, funders, and energy types, as well as the challenges and opportunities associated with these systems in providing electricity to customers. Though there might be some parameters that were not covered in this process, it provided a starting point for further research. This survey was conducted between May and September 2019, with updates completed by June 2022.

b. Qualitative interviews as case studies of two mini-grids in Malawi.

Two mini-grids, the Bondo and Chipopoma hydro mini-grids, were chosen for a more detailed study out of the 19 mini-grids identified. The reason for selecting these sites was their high level of community participation in their management, which is considered a measure of the sustainability of mini-grid projects [33]. The Bondo Mini-grid system comprises three power plants located on the Luchenya River in the Mulanje District of Southern Malawi. Bondo 1, rated at 60 kW, became operational in 2014 and obtained its full license in January 2016. Bondo 2, rated at 60 kW, was installed in 2017 and underwent repairs after flooding in 2020. Bondo 3, rated at 100 kW, was established in 2018. On the other hand, the Chipopoma hydro mini-grid is located in the Northern part of Malawi, over 800 km from Bondo, and it has a generation capacity of 36.5 kW, with immediate room for upgrading to 50 kW through a bigger gate valve. However, unlike Bondo, Chipopoma does not have a siltation chamber and forebay, and only in early 2022 was a dump load of 66 kW incorporated. As of June 2022, the system only served eighty-five houses, one maize mill, and several grocery shops.

The interviews were conducted with employees at MEGA and a volunteer at Chipopoma. Several visits were made to both sites. For Bondo, five field visits were undertaken on 16–20 May 2019, 18–22 February 2020, 5–9 February 2021, and 29 November–3 December 2021, with the final visit in June 2022. During these visits, interviews and discussions were conducted with the General Manager, Technical Manager, Project Coordinator, and technicians. Three visits were made to the Chipopoma mini-grid on 27–29 April 2020, 26–28 October 2021, and 14–16 May 2022. During the visits, observations of the whole catchment area, from the inlet to powerhouses and various villages, were also carried out. The following questions guided the interviews:

1. How was the idea of setting up the mini-grid in this area conceived in terms of the installed capacity and general design?
2. What were the necessary steps and regulations that you followed in setting up the mini-grid?
3. How was funding secured, and who provided the funding?
4. How is this system managed, and how many employees does the provider have?
5. What are the challenges faced by the system in the delivery of electricity to its customers?
6. What are the opportunities that are available for the system?
7. How many households, businesses and social sectors are connected to the system and how are tariffs structured?
8. What has been the government role of the Department of Energy and MERA as the regulator for the support, financial or otherwise, of the system?
9. Do you have any suggestions on how the mini-grid can thrive presently and into the future?
10. What are the survival strategies that you have employed to operate so far?

3. Results

The survey found 19 mini-grids in Malawi with the locations shown in Figure 1.

Table 1 summarizes the mini-grids database in Malawi. The mini-grids include Wovwe hydropower, which can be connected to the national grid or which can operate in isolation. Two systems generating power from bagasse as residues from sugar manufacturing have been included because the electricity is extended to the households of the employees.

According to Table 1, more than 94% of the total installed capacity is utilised, with only the abandoned systems not functional. However, most of the power generated, which comes from bagasse, is used as heat for processing. The electricity generated is primarily for the companies and their employees and not for the benefit of the local community. It is worth noting that 4.5 MW out of 4.76 MW of hydropower generated comes from the utility-owned system at Wovwe, which can be connected to the national grid or used as a mini-grid. The active solar PV/diesel hybrid is used to serve the islands of Likoma and Chizumulu on Lake Malawi. The hydropower systems at Usingini were abandoned due to a lack of financial resources. The six solar PV/wind hybrid systems were the first mini-grids to be developed in the country. However, they failed to survive beyond the pilot phase due to an undefined business model, lack of community engagement, politicians using the systems for their political gains, and failure to generate enough income for operations and maintenance.

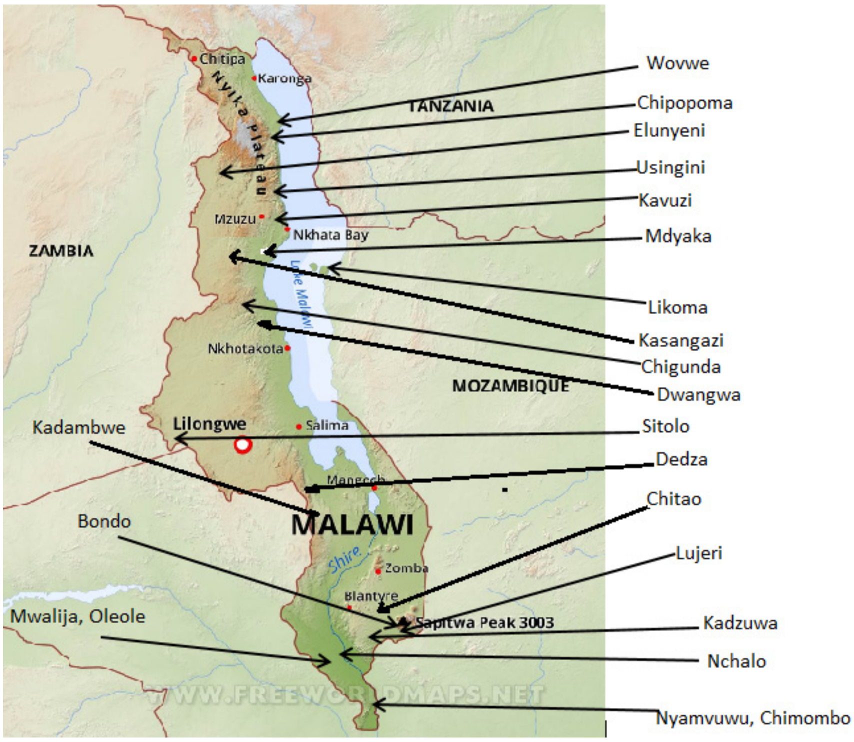

Figure 1. Map of Malawi showing location of major mini-grids in Malawi: Source [34].

Table 1. Compilation of mini-grids in Malawi together with challenges and success factors.

No.	Name of Case	Energy Source	Main Financiers	Status	Installed Capacity (kW)	Enabling Factors	Challenges
1	Bondo	Hydro	Practical Action, EU and OFID	Active	220	Community and donor support still available	Reduced water flow in dry season, hence low power Financial sustenance still a challenge
2	Chipopoma	Hydro	Naomi Oppriecht, UNDP and GEF	Active	35	Community and donor support still available	Low generation capacity Little room for expansion Reduced water flow in dry season
3	Usingini	Hydro	Practical Action	Abandoned	300	Potential anchor load available Community support	Lack of financial support to offtake
4	Kavuzi	Hydro	UNDP and GEF	Under construction	50	Donor support Close to Mzuzu city for recruitment and retaining of skilled technical and management staff	No prior promotion of productive use of electricity (PUE) Lack of financial support to offtake
5	Wovwe	Hydro	Germany and Malawi Government	Active	4500	Government owned and supported Skilled personnel readily available Tariffs subsidised	Reduced water flow in dry season, hence low power
6	Likoma	PV/Diesel	Malawi Government	Active	1300	Government-owned and supported Skilled personnel readily available Tariffs subsidised	

Table 1. *Cont.*

No.	Name of Case	Energy Source	Main Financiers	Status	Installed Capacity (kW)	Enabling Factors	Challenges
7	Nyamvuwu	Solar PV	EU and Practical Action	Active	30	Enhanced community participation	Financially unsustainable Low power produced
8	Mwalija	Solar PV	EU and Practical Action	Active	15	Enhanced community participation	Financially unsustainable Low power produced
9	Chimombo	Solar PV	EU and Practical Action	Active	15	Enhanced community participation	Financially unsustainable Low power produced
10	Oleole	Solar PV	EU and Practical Action	Active	15	Enhanced community participation	Financially unsustainable Low power produced
11	Sitolo	Solar PV	UNDP, GEF	Active	80	Donor and community support available	Financial sustenance still a challenge No anchor load
12	Kadzuwa	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable No definite business model in place Politically influenced
13	Chigunda	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable Failure to replace batteries and inverters Politically influenced
14	Mdyaka	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable No definite business model in place Politically influenced
15	Kadambwe	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable No definite business model in place Politically influenced
16	Elunyeni	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable No definite business model in place Politically influenced
17	Chitawo	PV/Wind	EU and Malawi Government	Abandoned	35	Community embraced the technology	Financially unsustainable No definite business model in place Politically influenced
18	Nchalo	Bagasse	Illovo Sugar Malawi	Active	11,500	Company supports the system	Community does not benefit from the system except employees of the company
19	Dwangwa	Bagasse	Illovo Sugar Malawi	Active	7000	Company supports the system	Community does not benefit from the system except employees of the company

During the study, it was found that of the five hydropower systems, three were active, one was under construction, and one was abandoned before completion. Of the eleven PV and PV/wind systems, five were active, while six failed to survive beyond the pilot phase. The other mini-grids were utility-owned or private company-owned; hence, their sustainability or resilience did not depend on the active involvement or contribution of the community. This indicated the probability of hydropower systems' survival being potentially higher than solar PV and or wind systems. This was mainly because hydropower systems do not need inverters and battery storage, which require replacement after their useful lives.

Bondo and Chipopoma were chosen from the 19 as case studies. Bondo is located in southern Malawi. It is a large mini-grid, generating 220 kW. Chipopoma is smaller, with 36.5 kW and is located in the northern part of Malawi. The Bondo mini-grid provided electricity to 17 villages in the Mabuka traditional authority area as of June 2022; see Table 2. The maize mills operate on a daily rostered pair system, meaning that only two mills are allowed to operate each day due to limited system capacity. The system has three power plants, with each having a dump load to handle excess power, which mostly occurs during the day and late at night; see Figure 2. The mini-grid has the potential to expand coverage. The electrical system is managed by the Mulanje Electricity Generation Agency (MEGA) with community involvement from the Village Electricity Committee. It was reported that the desktop studies and on-ground surveys conducted by MEGA showed that with the increased installed capacity of the plants and improved connection logistics, over 10,000 non-connected dwellings in the nearby Lichenya and Lujeri Valleys could be connected. This is in addition to various small businesses and social facilities for health and education.

Table 2. Comparison of Bondo and Chipopoma hydropower mini-grids.

Hydropower System	Installed Capacity	Households Served	Productive Uses	Other Uses
Bondo	220 kW	1600	8 maize mills, other small businesses	Health centre, schools
Chipopoma	35 kW	85	1 maize mill	Grocery shops

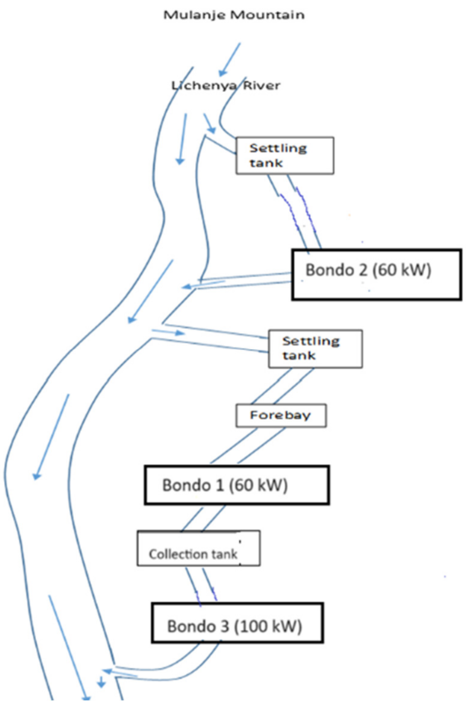

Figure 2. Schematic diagram of Bondo mini-grid: a map of the mini-grid can be found at https://www.mega.mw/activities/technology, accessed on 25 May 2024.

The Chipopoma mini-grid is located in Rumphi District, north-west of the University of Livingstonia; see Table 2 and system schematic Figure 3. The demand was so huge that several houses were not connected due to capacity and lack of equipment. It has a resistive dump load to take care of excess electricity. Chipopoma is managed by its founder, John Sailess, and supported by three other employees. Community members were involved in the management of the system through chiefs. The visits and interviews conducted in Bondo and Chipopoma highlighted the challenges and success factors that impacted the effectiveness of mini-grids in Malawi. These factors are discussed in the following sections.

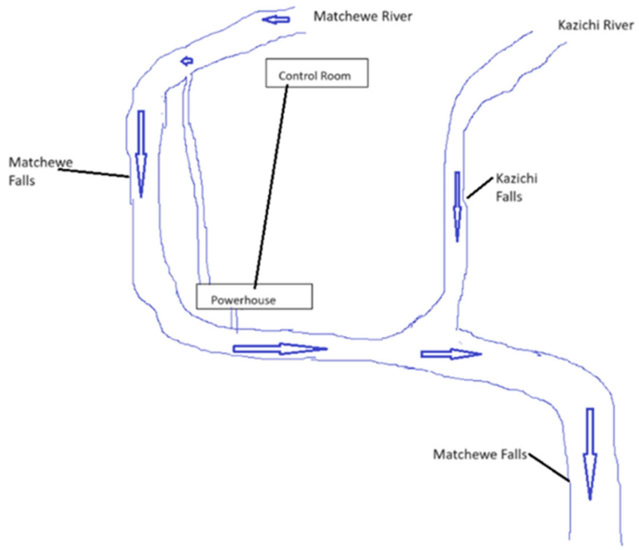

Figure 3. Schematic diagram of Chipopoma mini-grid hydropower.

3.1. Financial Challenges

Bondo and Chipopoma systems were developed with community, donor, and private funding. Funds for operation and maintenance come from electricity sales, community contributions and donor funding. Government support is missing, and income from the sales of electricity has not been enough to cover the operation costs for both mini-grids.

The electricity sales for Chipopoma have not been sufficient, and its sustainability is dependent on well-wishers, community members' contributions and volunteering by its founder, John Sailes. Even the three other members of staff are not paid salaries that benefit what they do. Such being the case, one investor in the area bought a maize mill for John Sailes so that he could earn extra money. The collection from electricity sales of MWK 297,500 (USD 291.55) is well below the average salaries in Malawi reported by Paylab, which is an international salary survey platform which puts salary plus bonuses for people in Malawi within the range of USD 124 to USD 416 (USD 270 on average) [35].

Bondo has an establishment of three managers, one senior technician, eight electricians, eight linesmen and eight watchmen. The collection from electricity sales of MWK 3,000,000 (USD 2951) is hardly enough for salaries and other benefits for employees. The salaries of key members of staff are supplemented by the Mulanje Mountain Conservation Trust (MMCT) as a parent of the Mulanje Electricity Generation Agency. This is because the managers are also involved in the activities of MMCT.

Figure 4 compares the mini-grid electricity sales and compares this to the average salary of USD 270 a month in Malawi to illustrate the fact that mini-grids do not generate enough income to support the staff.

There was an attempt to use meters for billing and charging an equivalent of USD 0.18/kWh, but this did not work as the meters failed to reset after being tampered with by users. A manifestation of the financial challenge faced by the system is the inability to mobilise repairs for one of the five transformers that were damaged by lightning. The replacement of the gate valve with a bigger one priced at MWK 550,000 (USD 541) was delayed due to financial challenges. A proper billing system and compatible meters can only be implemented with readily available finances, which is not the case. Bondo is also failing to start a contract with mobile companies to simplify the procurement of electricity units by customers. The estimated cost to provide a platform for buying electricity units using mobile money is USD 35,000, which is approximately one year's total income from electricity sales. Electricity sales and community contributions can provide sufficient funds for the day-to-day management of the system. However, major repairs and upgrades require external funding and technical assistance.

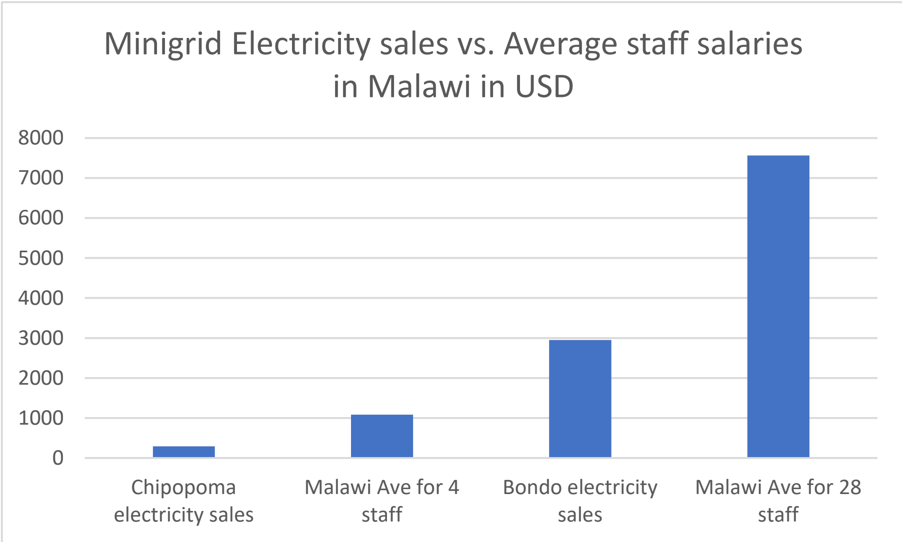

Figure 4. Comparison of mini-grid electricity sales with average income in Malawi.

3.2. Technical Challenges

The two mini-grids have been on a learning curve with regard to technology. The original arrangement was to generate power at Bondo 1, and then the discharged water was channelled for power generation downstream at Bondo 3. Bondo 1, which was the first to be installed, has a three-jet Pelton wheel that had some challenges with power generation, especially during the dry season. It required a lot of water, but little power was generated. As a result, the water from the penstock was allowed to pass Bondo 1 without driving the turbine, only to have power generated at Bondo 3. During all the site visits, Bondo 1 was idle. Documents from the energy provider at Bondo show that the flow rate at Bondo 1 and Bondo 3 is 0.261 m^3/s with heads of 50 m and 55.8 m, respectively. The head at Bondo 2 is 80 m. Crossflow turbines are the preferred turbine for these conditions, and these are being used at Bondo 3 and the recent upgrade to Bondo 2, which is furthest upstream. In addition, there has been a failure to replace damaged poles and delays in repairing a leaky canal. The low load factor at Bondo prompted MEGA to procure a Brickette-making machine; see Figure 5.

Figure 5. Unused briquetting machine (source V. Mwale).

The machine took advantage of excess electricity to convert dried plant waste into brickettes for free. This was a way of encouraging community members to have reduced reliance on firewood and turn to any dried plant matter. The project failed due to too much fat in the feedstock, which was brought accompanied by stones and metals, resulting in damaged screens. The machine remained idle for over four years.

Chipopoma has had its own learning curve regarding the technology part with its first penstock, which was made of high-density polyethylene and damaged within less than six months of operation. The damage was attributed to low strength and under-sizing. The UNDP, under the project of *Increasing Access to Clean and Affordable Decentralised Energy Services in Selected Vulnerable Areas of Malawi*, then provided the plant with a proper-sized metal penstock. Standard poles, cables, control units and transformers came along as part of the support from the UNDP. However, the gate valve from the intake to the turbine was not replaced, and this limited the flow for increased power production. With a properly sized gate valve, generated power could increase up to 50 kW from 35 kW, which was generated as of June 2022. A Pelton turbine manufactured in Malawi was initially installed, but this also broke down and was replaced several times by fabricated turbines from used motor vehicle wheels; see Figure 6. Two of these were manufactured so that if one failed, the other one was fitted while the broken one was sent for maintenance. This ensured that the electricity supply was largely uninterrupted.

Figure 6. Challenge of replacement parts: original turbine replaced with improvised rim-welded turbine device (source V. Mwale).

Sand and silt may accumulate within the system at Chipopoma as no siltation chamber was installed. A brick-and-mortar water tank was established in the powerhouse as a dump load, but cracks formed in the tank. This was rectified with the continuous flow of cold water into the tank.

3.3. Regulation and Registration Challenges

There are plans to upgrade Bondo from 220 kW to 6.5 MW with support from Vilunga Power with the new plant to take advantage of the storage of water. The paperwork was submitted to the Power Market Limited (PML), and the approvals were completed in April 2022, over 10 months from the date of submission. Similar delays were experienced with the proposed Usingini Hydropower Power Plant, which led to the abandonment of the power plant after Practical Action, as the facilitator, pulled out of its operations in Malawi.

The other regulatory challenge is tariff adjustment. Systems with the actual production of 50 kW or greater require approval from the regulator. Delays, amendment, and rejections for price adjustments happen based on the completeness of the application documents and the notion of protecting customers. Bondo used rates that were not financially viable for the operator in the absence of approval and regardless of the inflation and local currency devaluation. An energy system of equal to or less than 50 kW was exempted from all other regulations except registration in Malawi [36]. Chipopoma's generation capacity did not reach 50 kW; hence, it was not subjected to rigorous regulation and tariff approvals. A higher tariff of USD 0.18 kWh (MKW183) was put into place when the system was installed in 2018, as approval from the energy regulator was not needed at the time. Challenges with meters and the billing system forced the system operator to settle for the flat rate of K2,500 per month from 2019, which was adjusted to K3,500 (USD 3.43) per month in August 2022. Bondo was using the approved tariff of K78 (USD 0.076) for domestic customers as of December 2022, which was lower than the average national approved tariff of K104 (USD 0.10) in use by the grid in December 2022.

3.4. Load Profile and Power Demand Management

Both mini-grids failed to meet the peak power demand for the following reasons: At Bondo, customers have their meters fitted with current limiters, and in order to obtain more usage, the customer was required to make a separate application. This means that connecting an appliance that draws a much greater current, such as a pressing iron or cooker, will result in the meter being disconnected from the mini-grid. In addition to this, as of August 2022, there were over 2000 households that had completed wiring and paid the connection fees but still did not have an electricity connection due to a lack of meters. Before the synchronisation of the three national power plants, which had only been completed in March 2022, blackouts were very frequent in several of the villages served, especially during peak hours from 5 p.m. to 10 p.m. If all households were connected and each customer could withdraw power based on their needs, the system could collapse as 220 kW, which is insufficient to support such a large number of houses.

There was also a project for a briquette-making machine to construct fuel blocks from plant residues for household cooking. The machine was supposed to take advantage of the off-peak demand for electricity in making briquettes. However, the machine was facing challenges of broken screens due to failure in sorting the raw materials that were coming with stones and sand. The other challenge was poor-quality raw materials that contained too much oil. The two challenges were more than enough for the machine to be abandoned.

At Chipopoma, over 400 households needed electricity connections, but only 85 customers were connected. The system did not have load limiters, and the system became overloaded during peak hours of 5 p.m. to 7 p.m. Because of this, the system reacted through reduced power generation from 35 to 28 kW; hence, a low current was delivered to customers. During the dry season, especially from September to November, water demand for irrigation upstream was high, and water flow in the river was reduced. The hydropower system did not receive enough water flow to produce power. During this time, the operators opted for the system to work at intervals when the intake gained enough water.

Trash accumulation is also a challenge during the rainy season, leading to the clogging of screens at the intake. All these challenges led to the system failing to provide enough continuous electricity to existing customers and connecting over 4000 households in the catchment area who were still without electricity connection.

4. Factors to Consider in Enhancing Resilience of Mini-Grids in Malawi

The database of mini-grids showed that there was a relatively small number of mini-grids with an installed cumulative capacity of below 26 MW in Malawi. The country had a relatively high insolation in the range of 5.0 to 5.79 kWh/m^2/year, and there were several areas with a mean wind speed of 5 m/s annually, although this tended to be seasonal, which could be exploited for additional solar PV and PV/wind hybrid mini-grids.

Furthermore, the country has many perennial rivers in hilly areas of Mulanje District in Southern Malawi and Chitipa, Nkhata Bay and Rumphi in Northern Malawi [37]. These rivers have the potential to increase the number of hydropower mini-grids, as the cloud and rain associated with the hills mean that, locally, there was a lower solar irradiance resource.

The factors that affect the resilience of both Bondo and Chipopoma mini-grids are similar to those that affect other mini-grids, which include policies and regulations, institutional frameworks, delivery models and financing, technological solutions, capacity building and cross-sector linkages [38,39]. The above factors are interrelated, and they are discussed below with relevant international best practices.

4.1. Financial

Financing, both as capital cost and operating cost, is a major challenge. The dependence on private and community contributions and private funding is not enough to ensure that the existing mini-grids operate smoothly. Public financing is needed for the support of mini-grids in Malawi. One country where this occurs is Indonesia, where mini-grids proliferated, with strong direct financing from public finances in the form of subsidies and grants with ownership, operation and maintenance transferred to the community after construction [38]. The speed of mini-grid establishment was rapid, and Indonesia was ranked among the top ten countries globally with the most installed mini-grids totalling over 583 in 2019 [2].

The sharing of costs for feasibility studies, environmental impact assessment and licensing between the developer and institutions with public finance is another option, as practiced in Nigeria and Tanzania [38]. This practice has enabled Tanzania to progress in mini-grid establishments with over 158 MW in 2018 [12], against Malawi's less than 19 MW as the cumulative installed capacity.

A dedicated credit line for off-grid electrification, including mini-grids, is another option, as was the case in Rwanda and Tanzania [38]. Tanzania had a USD 23 million World Bank credit line, which was initiated in 2010. This was provided to the government-owned Tanzania Investment Bank for on-lending to local commercial banks as a 15-year low-interest debt for funding of up to 85% to developers of projects of 10 MW or less. However, only USD 5.77 million was disbursed by the termination year of the credit line in 2016. Four small hydropower projects totalling 7.2 MW were realised [13,38]. The large credit line was not utilised by the termination year of 2016 for reasons not disclosed by the authors. The 7.2 MW that was added and the learning curve on the implementation of such projects can still be regarded as a positive development.

Another example is Vietnam, where the government prioritised electricity as one of the socio-economic developments for communities, provinces and districts [40]. To support the imitative, several sources of financing were made available and productive use of electricity (PUE) was one of the priority areas.

Public finance through the Rural Electrification Fund (REF) and dedicated credit finance to developers in Malawi could have pushed the total generation capacity of mini-grids to greater levels and helped to alleviate the financial issues faced by mini-grid operators.

4.2. Technical

Technical challenges were closely linked to financial challenges. of the undersized penstock at Chipopoma and the identified need for a bigger gate valve would not have been issues had proper preparatory work with the involvement of experts taken place. Hydropower is a very mature technology, and the challenges of different turbines with different operating conditions are well known. Hence, the decision between cross-flow or the three-jet Pelton wheel should not have been a problem. Many of the technical issues could be solved using standardised equipment and expertise. Also, attracting technical expertise can be solved by financial availability, which can attract properly educated and well-experienced personnel. This can be addressed through public financing (such as grants, subsidies and matching grants) and dedicated credit facilities.

4.3. Regulations

Mini-grids should not be viewed in the same way as the main electricity grid, as is currently the case in the country [37]. There is a need for a simplified regulatory framework. In Malawi, the developer has to obtain approval from Power Market Limited; then, they have to be licensed by the energy regulator and obtain clearance from the Environmental Department. For hydropower, the developer is required to obtain water rights from the

Ministry of Water and Sanitation. This requires time and resources, and delays in the approval process are very common. Licensing and environmental clearance could be accelerated through a one-stop process within the Ministry of Energy, which includes all the requirements.

There is also a need to specify the minimum size of mini-grids that require licensing with smaller systems only requiring registration. The regulatory framework for mini-grids in Malawi specifies that mini-grids with an installed capacity of 50 kW or more require licensing [36]. Such a figure is on the lower side as licensing also means that tariff adjustment has to be approved by the regulator, among others. The approval can take a long time, and the tariff applied may be adjusted, which would not be cost-reflective in some cases; hence, it hampers financial viability. The country does not have a master plan as to which areas need to be serviced by mini-grids and which by the main grid. There is also a lack of planning on what is to happen if a utility encroaches on the area serviced or planned for mini-grids.

Neighbouring Tanzania, which has the second highest estimated installed capacity of mini-grids in Africa, at 158 MW [12], and as many as 49 hydropower mini-grids [13], offers many lessons on regulation. For example, small-scale power producers, with a capacity of 1 MW do not require a license from the regulator in Tanzania [19,41]. In Rwanda, projects aimed at generating less than 500 kW do not require environmental clearance or licensing (Energy Environment Partnership, 2018). The Tanzanian regulation specifies that energy projects generating less than 100 kW do not require tariff approval [19]. Developers are encouraged to collaborate with communities or customers over how much should be charged. Energy developers with an installed capacity of less than 100 kW of electricity are allowed to sell electricity to the utility in Tanzania [13]. The developers sell their electricity to the utility for USD equivalence to avoid loss of value with their local currency. In Tanzania, by law, a utility must pay the mini-grid operators the capital cost minus the subsidy upon arrival of the main grid. In addition, a mini-grid can also opt for conversion to a Small Power Producer (SPP) or a Small Power Distributor (SPD). Malawi could learn from these examples from neighbouring countries to simplify existing regulations and define new regulations that can help encourage investment in mini-grids.

4.4. Load Profile and Power Demand Management

The power plant fails to meet the power demand during peak hours, and the power-generating equipment is mostly idle during off-peak hours. The minimum usage is 40 kW, while the maximum usage is 110 kW, which ranges from 5 p.m. to 9 p.m. With a total installed capacity of 220 kW, several options are available for increasing the load factor, which are discussed below.

The KeyMaker Model (Bloomberg NEF, 2020) [42] is reported to be one way of improving the average revenue per user (ARPU). Under this model, the developer, or any other interested party, can be engaged in procuring raw materials or products from the local community, which are then used in mini-grid electricity to process them and sell them at a higher price to customers in urban areas. The Bondo Community and Mulanje District as a whole are well known for their abundance of pineapples almost all year round, and previously, there was a canning factory within the district. Establishing a factory for the production of jam, marmalade and juices from pineapples, among other fruits, with the use of mini-grid electricity, mostly during off-peak hours, could be an appropriate solution to this.

With no prospect of an anchor load for the two power plants, the productive use of electricity (PUE) needs to be intensified as a way of stimulating the customers' power consumption and capacitating them to pay for electricity. PUEs are a set of activities that use energy/electricity to increase income and productivity [19,43]. Such activities should also be able to add value, like taxation in the form of value-added tax. Examples include agri-processing, such as milling; light manufacturing industries like carpentry, tailoring, welding and looming; and the services sector, including bars and restaurants that need power for lighting, sound systems and refrigeration. The successful implementation of PUE requires addressing several challenges, including access to finance and equipment, good road networks, and the provision of technical and business skills in the local community. Such a wide range of needs cannot be left to the developer only, and other stakeholders such as financing institutions, equipment manufacturers/distributors, academia, government departments and the community need to be involved.

4.5. Capacity Building and Cross-Sector Linkages

The setting up and operations of mini-grids require adequate technical, planning and operational capacity. Mini-grids are often located in rural areas that have difficulties in attracting the required managerial and technical staff. The Bondo mini-grid is around 16 km from the district headquarters, and all its managerial and technical staff are based at the headquarters. This makes the arrangement costly and challenging to respond to issues in a timely manner. Poor mobile phone networks also hamper communications. The purchase of electricity units by customers becomes a challenge as the money is collected, and then tokens are generated at the offices at the district headquarters before being delivered to customers. In some cases, such an arrangement takes several days before a customer can access the electricity units. Chipopoma's experience is also the same and is solely dependent on the commitment of its founder to solving all technical and managerial issues. However, this system was located closer to the University of Livingstonia, which makes it easier to recruit and retain technical personnel. However, the challenge remains regarding financing for the reasonable remuneration of the technical personnel. Better approaches are needed to bring the right personnel and build the capacity of the personnel that are already available. This requires a financial commitment, whether from private, donor or public funding.

4.6. Institutional Frameworks

Malawi supports rural electrification through the Rural Electrification Fund (REF), a levy collected from the sale of all forms of energy. There is also the Rural Electrification Management Committee consisting of senior civil servants, who are accountable to the responsible minister who is mandated to develop rural electrification plans and implement rural electrification activities [15,37,44]. However, mini-grid technologies are not the recognised option within the rural electrification plans and activities, and they have not been able to access finances from the funding [37]. Because it is managed within the civil service, the REF has been hindered by transparency and accountability issues and many cases of corruption and diversion of funds [45,46]. The hope for public funding is contained in the energy policy of the Malawi Government [47], which recognised the following need:

> "To improve the management governance for Rural Electrification and Renewable Energy. . . Establishing a Rural Electrification Agency as a semi-autonomous legal entity to manage the Rural Electrification Fund and Rural Electrification activities (in both grid extension and off-grid options). . . 2018–2020"

The realisation of the need for the institutionalisation of a Rural Electrification Agency (REA) can go a long way to enhancing the management and transparency of the REF. Although the policy stipulates that the REA had to be institutionalised by 2020, this was not carried out as of November 2022. As explained by the energy policy, the establishment of the REA has the advantage of enhancing transparency and accountability of the REF, apart from attracting external funding from donors and the private sector, among others. Such an approach can increase the coverage of rural electrification and increase installed capacity. Neighbouring countries and others, such as Kenya, Tanzania, Zimbabwe, and Zambia, already have well-established REAs.

The rural electrified households lack demand for electricity, and they are unable to pay for electricity, or they are unwilling to pay, which affects the financial sustainability of electrification projects [48]. One way forward is to have rural electrification access programmes promoted along with PUE. PUE programmes can include raising awareness, increasing the availability of electricity, providing affordable energy-efficient appliances, providing financial support, offering extension services for enterprises or supporting modern farming. How a rural electrification programme was seen as a way of reaching last-mile electrification was carried out in Brazil [30]. Communities were engaged to conduct the following:

- Identify possible productive uses of electricity;
- Conduct awareness campaigns;
- Collaborate with universities, developers, regulatory agencies, and research centres;
- Take advantage of cross-subsidies to make electricity affordable and compensate providers for serving rural areas;
- Provide electrical appliances amongst the schemes.

Such comprehensive support increased family income by up to 250% due to increased productivity in farming and food processing [30].

In Ghana, the provision of electricity was combined with business training and the establishment of light industrial zones. As a result of the support provided to industrial zones, 550 companies were created, employing a total of 1970 people [43]. In Kenya, the promotion of PUE was conducted through customer education and partnerships established between the communities and providers/manufacturers of equipment, financial institutions and other stakeholders [43]. In Zimbabwe, a revolving fund was established to provide loans to new and existing rural households to support the purchase of electrical machinery from small-scale businesses. Financing from donors and public funding is needed for PUE programmes. Further development of the industry requires more support in understanding the production, demand and the whole value chain.

There is also a need for centrally available information regarding the electrification status in the country, such as the location of local energy resources, current grid infrastructure, the location of current mini-grids, off-grid electrification projects, and mini-grid opportunities. For example, Tanzania had a mini-grid online portal which was supported by the international finance institution but collectively managed by the REA, regulator, environmental agency, utility and Bureau of Standards [13]. Information on licensing, financing, the literature and the GIS resource siting map were available for the planning and execution of mini-grid establishment. Malawi has disjointed information; hence, there should be an effort made to provide all information on mini-grid opportunities, among others, under one portal or website.

5. Implications

This study's findings on mini-grids in Malawi have significant implications for policymakers, investors, and practitioners involved in the energy sector. This study highlights the critical role of public financing in supporting mini-grid projects and points to successful models from Indonesia, Nigeria, Tanzania, and Vietnam, where public funding, subsidies, grants, and credit lines are pivotal in the rapid establishment of mini-grids. In addition, the study recommends dedicated credit lines and cost-sharing mechanisms for feasibility studies to alleviate the financial challenges faced by mini-grid operators in Malawi. Addressing technical challenges requires standardised equipment, expertise, and economic availability. The study suggests that public financing, through grants and subsidies, could attract qualified personnel and ensure the proper implementation of mini-grid projects. To mitigate technical issues, this study advocates emphasising standardised equipment and involving experts in preparatory work. Moreover, this study suggests a simplified regulatory framework for mini-grids in Malawi. Learning from neighbouring countries like Tanzania and Rwanda, which have more streamlined regulations, Malawi could benefit from specifying different licensing requirements based on mini-grid size. This study highlighted the need to have an REA institutionalised as soon as possible and take charge of the utilisation of the REF. Lastly, this study proposes establishing a one-stop process for approvals within the Ministry of Energy to expedite the licensing and environmental clearance processes.

6. Conclusions

The mini-grid sector in Malawi is facing many challenges, with little progress on sustainable development and low-carbon energy transitions in rural areas. The installed capacity of active mini-grids in Malawi is not encouraging when compared to that of some of the neighbouring countries, such as Tanzania. The number of beneficiaries in Malawi is small, encompassing hundreds of families, whereas the need is in the millions for people lacking access to electricity in both rural and urban areas of Malawi. The lack of knowledge and awareness of the population was decisive in why several projects were abandoned, and this needs to be addressed.

This paper has identified the common challenges for implementation by compiling a database of mini-grid projects in Malawi and developing case studies for the Bondo and Chipopoma hydro mini-grids. The sustainability and resilience of mini-grids in Malawi depend on addressing financial, technical, regulatory, and institutional challenges through a coordinated and well-funded approach. One of the major issues of these mini-grids is financial instability. They struggle to cover operational costs from electricity sales alone. This hampers infrastructure maintenance and service expansion. The low financial return of the mini-grids is tied to the non-productive use of electricity. Encouraging the use of electricity for productive activities, like agro-processing, can stimulate local economies and increase the financial sustainability of mini-grids. In addition, public financing through dedicated credit lines and subsidies can simulate mini-grid electricity usage.

Technical challenges, such as undersized equipment and insufficient technical expertise, are closely linked to financial constraints. Addressing these challenges requires standardised equipment, proper initial design, and the involvement of technical experts. Furthermore, attracting and retaining skilled personnel necessitates adequate financial resources, underscoring the need for robust public and private financing mechanisms. Simplifying these regulations, as seen in Tanzania and Rwanda, where smaller projects are exempt from rigorous licensing requirements, could streamline development processes. Establishing a one-stop process for approvals within the Ministry of Energy could expedite these processes.

Managing peak power demands remains problematic, leading to frequent outages. Bondo and Chipopoma mini-grids cannot meet peak power demand, leading to frequent power outages and user dissatisfaction. Implementing strategies like the KeyMaker Model, which promotes the productive use of electricity during off-peak hours, can enhance economic viability and efficiency. Strengthening institutional frameworks, such as establishing a Rural Electrification Agency (REA), can improve the management and transparency of rural electrification efforts. By learning from international best practices, Malawi can enhance its mini-grid systems' reliability and coverage, promoting sustainable development and improving rural communities' quality of life.

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