Performance analysis of solar micro-grids in rural developing areas

A case study in Sierra Leone

MSc thesis Complex System Engineering and Management

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Preface

Dear reader,

In front of you is my thesis about the performance of solar micro-grids in rural developing areas, a topic I have researched for the past months. When I was exploring bachelor programs, the study of Technology, Policy and Management caught my attention because of a story shared by a student who had conducted research on solar panels in a developing country. From that moment, I knew that this was what I wanted to do. It perfectly aligns with my interests in societal challenges, developing countries, and sustainable energy. In our current society, we often forget that electrification problems exist, but it remains a significant issue nowadays. For me, it is an honour to contribute to an issue that many people around the world still face. I am very grateful that, in the final phase of my studies, I have had the opportunity to realise this dream, fully immerse myself in rural electrification, and make a meaningful societal impact.

I am deeply grateful to my supervisors for their support and guidance. Dr. Ir. P. W. Heijnen, thank you for all the weekly meetings, they helped me greatly in navigating my research. I also appreciated your calm and structured approach, which often allowed me to leave your office without stress. Prof. Dr. M.E. Warnier, thank you for your ideas and meetings that helped me find the right research direction. Finally, Maarten, I am very thankful, without you, I would not have been able to work on this amazing project and experience Sierra Leone firsthand. I am also grateful for the social insights you provided, which complemented my knowledge. A final thank you goes out to my friends and family who supported me during the process of my research. I have put a lot of energy, effort, and enjoyment into this thesis, and all that remains for me is to wish the reader a lot of reading pleasure. Enjoy reading it!

Liselotte van de Beek
Delft, October 2024

Summary

Ensuring access to affordable, reliable, and sustainable energy for all is one of the Sustainable Development Goals. Despite this, 675 million people globally still live in the dark, with rural areas facing the biggest challenge. Sierra Leone exemplifies this issue, with only 4.9% of its rural population having access to electricity. The lack of access hinders economic and social development, affecting healthcare, education, and overall quality of life. While grid extension remains expensive and difficult to implement in remote locations, solar-based micro-grids offer a promising solution for rural electrification, leveraging Sierra Leone's significant solar energy potential.

However, literature reports performance issues with these micro-grids. Factors that can influence micro-grid performance are identified in the literature, but their impact and potential mitigation strategies remain under explored, especially in rural contexts. The research aims to identify and classify factors affecting micro-grids performance and assess their impact on deployed micro-grids in rural developing areas. This research ultimately provides insights into mitigation strategies on the micro-grid performance in rural developing areas, considering the technical, social, economic, and governmental environment. This bridges the gap between quantitative and qualitative research in this field, to ultimately improve access to electricity in rural areas.

This thesis addresses the research question:
Which factors impact the performance of micro-grids in rural developing areas, and which mitigation strategies can improve the access to electricity?

The scientific contribution to creating a generalised approach for micro-grids in rural developing areas, based on a case study in Sierra Leone. This to ultimately improve access to electricity in rural areas. The approach of this study is a combination of the case study methodology and the modelling methodology. The case study for data collection, including literature review, site visits, observations, and stakeholder interactions through semi-structured interviews with community members and experts. The modelling approach uses the simulation tool Python for Power System Analysis (PyPSA) to quantitatively assess the impact of identified factors and mitigation strategies on micro-grid performance without disrupting actual systems. PyPSA is chosen for its suitability in modelling complex energy systems, considering the physics of power flows. This dynamic modelling approach provides a realistic representation of micro-grid operations, allowing the testing of experiments. The mixed-methods approach enables comprehensive research of the technical, social, governmental, and economic factors influencing micro-grid performance in rural areas.

The case study focuses on four small communities in Sierra Leone with varying levels of user satisfaction and grid performance. Findings highlight a complex actor situation, revealing that micro-grids perform under limited economic resources, technical constraints and government dependencies. Grid operators wait for tariff increases to cover operation and maintenance costs. The government has not taken action, as users indicate that the electricity price is too high, reflecting the rigid nature of the current situation. The grid operators have high expectations of funding organisations, but these organisations argue that operational and maintenance costs are no longer their responsibility.

The performance of micro-grids is measured in the average number of hours electricity is unavailable, this is based on the semi-structured interviews and the Multi-Tier framework. The Multi-Tier framework outlines performance indicators with associated requirements for micro-grid operation. The electricity availability is one of the the performance indicators in the multi-tier framework. In this research, the Key Performance Indicator is the average number of hours electricity is unavailable in Loss of Load Expectation (LOLE) hours.

System requirements are formulated from the semi-structured interviews combined with the Multi-Tier framework. This establishes two system requirements: a maximum of 8 LOLE hours per day (day requirement) and a maximum of 8 LOLE hours per night between 19:00 and 07:00 (night requirement).

The night requirement is the most critical as it focuses on maintaining electricity during evening hours, extending users' productivity.

Different factors can influence the performance of micro-grids. Factors frequently cited in the literature that influence micro-grid performance have been identified and classified into social and technical categories. Key technical factors include system design, local technicians, and exceptional events, while social factors encompass community behaviour, ownership, and system security. Three relevant factors are identified, based on the frequency of occurrence in communities and mentioned in expert interviews: high use of appliances, the low design quality of batteries and the lack of technicians.

The most relevant factor in this study is determined by the extent to which it affects the availability of electricity. The most relevant factor in this research is the quality of the battery in terms of battery performance. The battery performance directly influences the electricity availability of all solar-based micro-grids. Another KPI in this research related to battery performance is the lifetime of the battery. The battery performance declines over time. The battery's lifetime indicates how many days the battery will operate. The degradation rate of the battery is determined using the fade curve. When the battery performance level impacts the system to such an extent that the micro-grid no longer performs within the system requirements, battery replacement is recommended.

Now the most relevant factor is the battery performance, the influence of battery performance on micro-grid performance is analysed. Simulation inputs include technical specifications, average solar generation profiles, and electricity demand patterns. The model's key output is the LOLE, analysed under different battery performance levels, and the battery's lifetime is also assets.

The current state of the micro-grid reveals that seasonal variations significantly impact the system's performance, particularly during the rainy season due to limited electricity generation. In contrast, the dry season presents no issues when the battery performs well, highlighting storage capacity as the limiting factor. It is also concluded that the battery has only half the expected lifespan due to its operation in the high temperatures of Sierra Leone.

The research evaluates different mitigation strategies: Demand Control (DC), air conditioning, and additional battery capacity. These strategies are chosen as they fit in the economical, technical and regulatory environment of the operating micro-grids. The strategies are the least-cost options, fits in the micro-grid configuration and the grid operators knowledge and do not need governmental support. These strategies are tested through multiple experimental runs to assess their potential in maintaining micro-grid performance under various battery performance levels.

Demand Control is considered as the mitigation strategy that can address electricity availability problems related to battery performance. DC is effective because it positively affects the electricity availability in two ways. It decreases the minimal battery performance level and it increase the electricity availability in evening hours, enhancing access to electricity in rural areas. Even if financial resources are available, DC remains an attractive strategy for providing electricity in the evening hours. However, to increase daytime electricity availability and extend the actual battery lifespan, adding storage is a recommended strategy. However, during the rainy season, additional storage capacity has a limited impact, as the main constraint is low solar generation. The capacity of deployed micro-grids in rural developing areas is too small to add air conditioning loads and therefore to use air conditioning effectively.

DC fits in the rural developing context. Clear communication of DC schedules is essential for managing expectations. The question remains whether DC is desirable for users. Further research is recommended to validate DC's effectiveness in practice, explore optimal timing and duration, and investigate the impact of DC on other relevant factors, such as high appliance use. Lastly, the combination of mitigation strategies can enhance the performance of micro-grids in rural areas, but further research is needed.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
CHC	Community Health Center
CoSEM	Complex Systems Engineering and Management
DC	Demand Control
DC	Direct Current
DG	Sustainable Development Goals
EDSA	Electricity Distribution and Supply Agency
EGTC	Electricity Generation and Transmission Company
EWRC	Electricity and Water Regulatory Commission
HDI	Human Development Index
KPI	Key Performance Indicator
LOLE	Loss of Load Expectation
RREP	Rural Renewable Energy Project
SoC	State of Charge

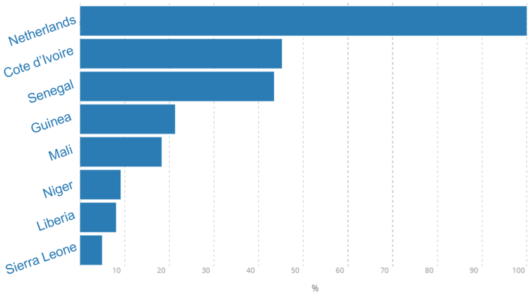
Symbols

Symbol	**Definition**	**Unit**
N	Set of all buses	
L	Set of all transmission lines	
T	Set of all timesteps	
S	Set of all storage	
R	Set of all generators	
S_n	Apparent power at bus, $n \in N$	kW
P_n	Active power at bus, $n \in N$	kW
Q_n	Reactive power at bus, $n \in N$	kW
$d_{n,t}$	Electrical load at bus, $n \in N$ at time, $t \in T$	kW
$g_{n,t}$	Dispatch of generator at bus, $n \in N$ at time, $t \in T$	kW
$h_{n,t}$	Dispatch of storage at bus, $n \in N$ and time, $t \in T$	kW
$K_{n,l}$	|N| x |L| Incidence matrix	
$f_{l,t}$	Power flow over the transmission line, $l \in L$ at time, $t \in T$	kW
$e_{n,t}$	Storage state of charge at bus, $n \in N$ at time, $t \in T$	kW
$h_{n,t}^{in}$	Total charge capacity at bus, $n \in N$ and time, $t \in T$	kW
$h_{n,t}^{out}$	Total discharge capacity at bus, $n \in N$ and time, $t \in T$	kW
$P_{l,t}^{loss}$	Transmission line losses for line, $l \in L$ at time, $t \in T$	kW
F_l	Transmission line capacity for line, $l \in L$	kW
H_n	Storage capacity at bus, $n \in N$	kW
η_1	Storage charge efficiency	
η_2	Storage discharge efficiency	
λ	Storage self-discharge rate	

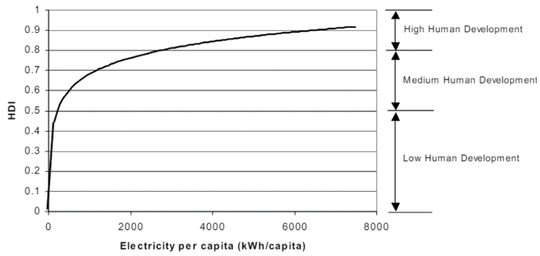
1 Introduction

Ensure access to affordable, reliable, sustainable and modern energy for all, is one of the 17 Sustainable Development Goals (SDG) adopted by the United Nations adopted in 2015 [1]. However, in 2023, 675 million people still live in the dark. Providing access to electricity remains a major challenge in many sub-Saharan African countries, where 75% of the global population has no electricity [2]. The limited accessibility of electricity occurs particularly in rural areas because these areas are far from the inhabited world and thus very difficult and expensive to reach [3].

Sierra Leone provides a relevant example of a country with an electrification challenge. The share of the population with access to electricity was 21.8% in 2022 [4]. The situation in rural Sierra Leone is even more dramatic, in only 4.9% of the rural population had access to some form of electricity in 2021 [5]. One of the lowest electrification rating in the world, see Figure 1.1a.



(a) Ranking of access to electricity in sub-Saharan African countries



(b) Human Development Index versus Energy

Figure 1.1: The need for access to electricity

Rural electrification is on the policy agenda in Sierra Leone. As part of its Medium-Term National Development Plan for 2019-2023, the government sets the improvement of electricity supply in rural communities on the map [6]. Electrification can lead to more economic and social development, affecting healthcare, education, and overall quality of life. It can improve the overall livelihood through the availability of light and the possibility of using more productive and safe technologies. Also, healthcare conditions will increase directly by improving Community Health Center (CHC) conditions [7], [8]. A correlation between the energy consumption of a country and the Human Development Index exist (HDI). This means that the development of poorer countries is linked to energy access. A low energy consumption leads to a low HDI. This again highlights the need for access to electricity, see Figure 1.1b [9].

National grid extension is a solution to electrify rural areas, but it is not always the fastest and most cost-effective approach due to the location of these areas [10], [11], [3]. Solar based micro-grid systems currently seem to be one of the most promising technologies for Sierra Leone. The country has over 2187 hours of sunshine a year. Solar radiation in the Netherlands is around 1050 kWh/m² [12]. This makes the market for small solar systems in Sierra Leone attractive [13], [14], [15].

A micro-grid is a system that operates independently of the main grid and supplies electricity over relatively small distances to the consumer. There exist on-grid and off-grid micro-grids. On-grid micro-grids are connected to the main grid and can use their electricity as electricity from the main grid. Off-grids are small independent power systems without main-grid connections which only produce the power near the point of consumption [16]. Off-grid micro-grids are economically feasible when the distance from the main grid is far enough, this is mostly the case for rural areas. The main reason for this is that the costs for extending the main grid are in these areas higher than building a micro-grid [17], [8].

The success of micro-grids has been confirmed in places such as India, Sri Lanka, Nepal, Indonesia and Tanzania [3]. It shows that the successful integration of micro-grids is influenced by factors such as government support and community organisation, which is essential to keep these systems operating over the project's lifetime. A promising setup could consist of solar panels and storage, with additional Diesel generators [18], [17]. This can be the least-cost way to provide access to electricity, due to the amount of sun hours and significant decrease in the cost of solar systems in recent times [19], [10].

The government established micro-grid regulations to promote rural electrification through renewable energy in Sierra Leone. These regulations streamlined requirements for renewable energy projects and aligned energy policies, making the investment climate more attractive for micro-grid initiatives. As a result, financial institutions, donors, and international organisations began investing in Sierra Leone's micro-grid projects [20], [21]. One of the investors is the United Nations Office of Project Services (UNOPS). This is through the Rural Renewable Energy Project (RREP), which aims to provide access to off-grid solar micro-grids in up to 97 communities in Sierra Leone. Findings show that the project was successful, increased, and higher connection rates to the micro-grids were observed, as 65% of the community houses wanted a grid connection [7]. The access to electricity enhances living standards and supports economic development in these areas. The available electricity in electrified Community Health Centers (CHCs) increased. The CHCs had 78% of the time electricity for at least 10 hours a day, compared to only 37% in communities without micro-grids[22].

Alongside the success, micro-grids face challenges. Economic challenges, as these communities tend to have low-income inhabitants [2], [18]. Some of the inhabitants of the researched communities find the cost of the unit of electricity too expensive [7]. In addition, there are technical challenges as the deployed micro-grids experience performance issues [2], [16], [23], [24]. The operation of deployed micro-grids based on renewable energy remains a challenge. It can be seen as a complex and multi-dimensional problem due to various factors at play, including technical, social, economic and governmental challenges.

1.1. Literature review

To gain an understanding of the current state of micro-grids in rural developing areas a literature review is conducted. This literature review focuses on the electrification of rural areas in developing countries with renewable energy-based micro-grids. This is a hot topic in the field of access to electricity, many recent studies are available and it is still growing. Based on this review, the research gap is identified. These gaps provide the starting point for this research and lead to the research question formulated in 1.2.

To search and select literature on the current state of micro-grids in rural areas, a multi-step approach is adopted. Firstly, an extensive search of Scopus and Google Scholar databases is conducted to explore available literature on the broader topic of renewable energy-based micro-grids as micro-grids can be addressed from a wide range of different perspectives, including technical, economic, social and governmental aspects of the system. Subsequently, a more focused search is performed to get insights into the performance and simulation of micro-grids in rural areas.

1.1.1. Optimal micro-grid designs

Electrification plans for countries in Sub-Saharan Africa have been widely examined, with most studies adopting a techno-economic perspective. Many of these studies focus on developing models and tools to determine the most cost-effective reliable system configuration for the deployment of renewable energy-based micro-grids. These models typically involve hybrid systems and evaluate trade-offs between diesel generators, renewable energy sources, and battery storage. Asuamah et al. propose the optimal configuration and size that includes photovoltaics (PV) and batteries based on cost considerations for a community in Ghana [8]. Similarly, Sankoh et al. conducted a comparative techno-economic research for a rural and remote community in Sierra Leone, identifying PV, diesel generators, and batteries as the most feasible options [18]. Odou et al. also find that a least-cost optimal system for rural Benin includes PV, diesel generators, and batteries [17]. These studies provide valuable insights into least-cost configurations for the deployment of rural micro-grids.

1.1.2. Performance analysis of deployed micro-grids

Over the years, many micro-grids have been installed in rural developing areas. However, after determining the perfect the micro-grids, the system's performance remains a challenge and performance issues still arise. Maintaining continuous operating micro-grids is important, as this increases community satisfaction and, in turn, the willingness to pay for electricity, which can ultimately enhance access to electricity [25].

Some studies have attempted to address these challenges by using modelling approaches for the performance analysis of existing micro-grids. For instance, Bukari et al. applied a techno-economic model to assess the design accuracy, power supply challenges, and financial viability of two micro-grids in Ghana and suggested diesel generators to ensure system reliability [26]. Similarly, Zebra et al. analysed a solar micro-grid in Mozambique and found frequent power outages due to system overload, primarily caused by high demand. They suggested the addition of a diesel generator backup to mitigate these fluctuations and ensure a reliable electricity supply [25]. Wassie et al. examined the actual performance of a micro-grid in Ethiopia compared to its estimated model performance, and concluded that the grid performs poorly. The grid produced only 1182 kWh/day compared to the estimated 2214 kWh/day, which they attributed to factors such as temperature and dust that were not accounted for in the model [10]. These modelling studies found poor grid performance and relate this to certain possible factors. However, these studies do not address the various factors that may affect micro-grid performance or the likelihood of these influencing factors occurring in rural developing areas. In addition, only the study by Wassie et al. used a simulation model to analyse system performance, while all the other studies mentioned above employed optimisation models [10]. It is all based on optimising the micro-grid instead of simulating and analysing the performance of micro-grid under different circumstances, leaving a gap in simulation-based studies for micro-grids in rural developing areas.

1.1.3. Performance analysis in social research

In addition to modelling research, social studies have explored factors that can influence micro-grid performance, using descriptive methods. Numminen et al. used a case study to identify factors such as the overloading of high-consuming appliances and performance issues caused by human intervention [16]. Ngowi et al. highlighted that the quality of components could significantly impact micro-grid performance [27]. Nuru et al. identified various social and technical barriers affecting micro-grids, such as long transmission lines leading to power losses and illegal connections disrupting the system [28]. In addition, Kapole et al. used a qualitative and quantitative approach to investigate factors related to performance issues, such as a lack of technical support, maintenance issues and poor system quality, but no simulation study is include [29]. These studies identify potential factors that may affect micro-grid performance, however, they lack performance analyses where the quantitative impact is determined.

1.1.4. Mitigation strategies in rural electrification

Most rural electrification studies fail to propose mitigation strategies to address factors that may affect micro-grid performance. Wassie et al. mentioned factors that could explain the gap between modelled and actual micro-grid performance but did not suggest strategies to reduce the impact of these factors [10]. Studies such as those by Jabir et al. and Ayesha et al. analyse the impact of demand-side management on the reliability of generation systems, but they do not focus on rural micro-grids in developing areas [30], [31]. Only Benavente et al. and Zebra et al. consider whether increasing battery capacity or solar panel size could improve micro-grid performance [32], [25]. This is from a point of few to find the best system size, using optimisation. These studies do not directly address more factors that influence micro-grid performance in rural settings. This indicates a clear gap in the development of strategies to mitigate the challenges of micro-grid performance in rural developing areas.

1.1.5. Discussion and Knowledge Gap

Previous research focuses on optimising micro-grid configurations in techno-economic terms finding low-cost reliable micro-grid systems. Other studies focus on improving the performance of already existing micro-grid with optimising models, since a majority of the corresponding articles address micro-grid performance issues in rural developing areas. Social research examines micro-grid performance and identifies various causes of performance issues, providing a list of factors that can influence micro-grid performance. However, a standard approach for identifying these factors is lacking, and simulating models that analyse the actual impact of these factors on the performance of micro-grids are missing. A simulation model is a representation of a system that is used to show and predict the system's behaviour under specific circumstances [33]. These analyses are crucial for identifying fitting mitigation strategies. Strategies to improve micro-grid performance exist. However, specific strategies that mitigate the effects of these influencing factors on micro-grid performance, while fitting the context of rural developing areas, remain limited, creating a significant knowledge gap. The development of such mitigation strategies is important for ultimately improving access to electricity.

This research aims to bridge the gap between social studies to address influencing factors and computational models for micro-grid performance analysis. It develops an approach to identify, simulate, analyse, and mitigate influencing factors and their impact on the performance of micro-grids in rural developing areas. Although this research focuses on a case study in Sierra Leone, the steps provide a general approach to micro-grid performance research in rural developing areas.

The main research question is as follows:

> *Which factors impact the performance of micro-grids in rural developing areas, and which mitigation strategies can improve the access to electricity?*

1.2. Research question and sub-questions

The literature review provides insights into the current state of micro-grids in rural developing areas and highlights the existing knowledge gap in this field of research. This knowledge gap is translated into the main research question, which identifies impact factors on performance and ultimately analyses the impact and mitigation strategies for the most relevant influencing factor. The research is structured into two parts: the first part identifies and validates influencing existing factors and their qualitative impact on the performance. The second part examines the quantitative impact and mitigation strategies of the most relevant influencing factor micro-grids in rural developing areas. Based on the main research question, a series of sub-questions are formulated.

Micro-grids in developing countries operate within environments shaped by various factors, including regulatory frameworks, economic conditions, technical characteristics, and social aspects. The specific context in which the micro-grids in rural developing countries operate is examined in sub-question 1:

> *SQ 1: What is the current situation of solar micro-grids in rural developing areas?*

After outlining the context. Key Performance Indicators (KPIs) are identified for micro-grids in rural developing areas, which make the performance of micro-grids measurable. For these KPIs, it is necessary to define specific system requirements in which the micro-grids must operate. These KPIs and system requirements are explored in sub-question 2:

> *SQ 2: What are the most relevant Key Performance Indicators and the system requirements for solar micro-grids in rural developing areas?*

Once the KPIs and their corresponding requirements have been defined, the factors that influence the performance of micro-grids in rural developing areas are determined.

> *SQ 3: Which factors affect the performance of micro-grids in rural developing areas?*

Now that the KPIs, system requirements, and influencing factors have been determined, the actual performance of typical micro-grids in rural developing areas is analysed.

SQ 4: What is the current performance status of micro-grids in rural developing areas?

Thereafter, from all the factors found in sub-question 3, the impact of the most relevant factor on typical micro-grids in rural developing areas is assessed. In this research battery performance is found as the most relevant factor, therefor the sub-question is as follows:

SQ 5: What is the impact of the battery performance on the performance of micro-grids in rural developing areas?

To mitigate the impact of the most relevant factor, the battery performance, strategies suitable for the rural development context are identified. Once identified, their effectiveness is assessed to recommend how to mitigate the impact of this factor that affects the micro-grid performance to in the end increase the access to electricity.

SQ 6: What are possible mitigation strategies within the rural developing context and what is the impact of these strategies on micro-grids in rural developing areas?

1.3. Relevance

Rural developing areas nowadays still have little or no access to electricity. The social relevance of this research is to increase the performance of micro-grids to ultimately increase the access to electricity in rural developing areas. This contributes to improving economic and social development, affecting healthcare, education, and overall quality of life.

The scientific contribution of this research is the development of a comprehensive approach that identifies, simulates, analyses, and mitigates external factors and their impact on the performance of micro-grids in rural developing areas. The approach is based on a case study of a deployed micro-grid in rural Sierra Leone and this is used to create a generalised approach for micro-grids in rural developing areas. In addition, this research contributes to studies analysing deployed micro-grids by providing a simulation model and it provides a socio-technical study which gives insights beyond only model-based or social research.

This research aligns with the Master Complex System Engineering and Management (CoSEM) program as an understanding of the social, governmental and technical field is needed to increase solutions for a world with access to electricity. Micro-grid systems are implemented in a complex environment, due to international, national and community-based actors with varying objectives. The research bridges the gap between technology and the social environment, between computer models and social conditions. This research is particularly in line with the energy track, as the thesis analyses the performance of solar-based micro-grids.

1.4. Thesis outline

In the following chapter 2, describes the research methodology. This research consists of two parts. Part one includes chapter 3, chapter 4, chapter 5, chapter 6 and chapter 7. In chapter 3 the specific case study is described to shape the static context for the micro-grid systems. chapter 4 the dynamic context of the micro-grids with various actors is explained. In chapter 5, another literature review is included to find influencing factors. After this, chapter 6 validates the influencing factors. The last chapter in this past, chapter 7, identified various strategies to mitigate performance issues. The second part of this research includes chapter 8, and chapter 9. In chapter 8 a micro-grid model is constructed and chapter 9 shows and discusses the results. Finally, the research ends with the conclusion including recommendations inchapter 10 and the discussion inchapter 11.

2
Research methodology

This chapter describes the research methodology for analysing micro-grids in rural developing areas. It explains the approach to collect data and to analyse the micro-grid performance. These steps lay the foundation for the approach used in this research.

2.1. Research approach

As discussed in 1.1.5 there is not yet an approach to simulate and analyse the performance of deployed micro-grids in rural developing areas. The selected research approach aims to identify and classify factors affecting micro-grids performance and assess their impact on deployed micro-grids in rural developing areas. This approach ultimately provides insights into mitigation strategies on the micro-grid performance in rural developing areas. To address this gap qualitative and quantitative research is needed where the simulation of the micro-grid ultimately helps to formulate recommendations.

The studies used in the literature review are mainly case studies, model studies, or a combination of both as research approaches. The literature review reveals that social studies are all based on case studies, as seen in the research by Ngowi et al., Numminen et al., Nuru et al., and Kapole et al. [27], [16], [28], [29]. Additionally, socio-technical and socio-economic studies predominantly use a combination of a case study as an implementation for the model study. For micro-grid with performance issues the studies uses optimising models to find the best system configuration. The literature review shows that Bukari et al. optimise a micro-grid through a model study combined with a case study of a micro-grid from Ghana [26]. Similarly, Zebra et al. follow this approach for optimising a micro-grid from Mozambique [25]. Only Wassie et al. used a simulation model with a case study to analyse a micro-grid in Ethiopia [10]. Based on these studies, this research adopts a case study approach combined with a modelling approach. A simulation study is employed for the modelling approach to address the gap in simulation-based studies for micro-grids in rural developing areas. This choice is made because nearly all the studies referenced in the literature review use optimisation models in the modelling approach.

This is the main framework for this research and allows a more comprehensive examination beyond technical models, enabling the identification of outcomes that are well-suited to the social context. For data gathering the case study approach is used. The modelling approach is used for micro-grid simulation and can provide a framework for addressing the impact of different factors. The main advantage of this approach is that system interventions can be simulated and tested without affecting the real system. However, ensuring a representation of the real world is a challenge in modelling. The consequence is that the output can be affected by the simplification of the model, leading to biased results. Thus, careful modelling is important by properly defining the scope and selecting the right elements to include in the model [34].

2.1.1. The case study

The case study approach is chosen due to its extensive use in the literature and its ability to gather specific data, helping to address data limitations and uncertainties in the rural developing context. This is helpful since systems in developing countries and rural areas face a lack of real-world monitoring data and many unknowns and uncertainties [10], [14].

Data gathering

The data collection approach is adapted from a three-stage framework provided by Painuly [35]. This approach can be used to identify external factors that influence the performance of deployed micro-grids. Useful data can be identified using the following approaches:

- *Literature review*
  The literature review considers similar micro-grid research to collect the already identified influencing factors that play a role in affecting the micro-grid performance. This review includes micro-grids in different countries and with different configurations. The collection forms a list of factors which can be used in further research. The list is used during the site visits to validate the occurrence of factors. The list is also useful during observations. Finally, the list is useful during the interaction with stakeholders to obtain specific information.
- *Site visits*
  Site visits provide an understanding of the micro-grid operation in real-world conditions and to collect new data and validate factors identified in the literature. Practical site visits to communities are conducted, during these visits the main tasks consist of interaction with stakeholders and observations.
- *Interaction with stakeholders*
  Lastly, the stakeholders perspective must be taken into account. This step is crucial as the perception of stakeholders helps in the identification of the influencing factors. Stakeholders may include users and experts such as operators and developers.

  The interaction is done by semi-structured interviews. In semi-structured interviews, the general story line exists, but depending on the interviewee response more in-depth questions can be asked. Semi-structured interviews are often used in social science research, particularly in contexts where flexibility is needed to explore diverse perspectives and experiences. Semi-structured interviews create inclusiveness by allowing an easy way for a wide range of community members to participate and share their stories, and the interviewing method can be adapted to the specific culture [36]. Numminen et al., Nuru et al., and Kapole et al., used in the literature review, use semi-structured interviews, indicating this fits in the context of developing countries [16], [28], [29]. The topics covered in each semi-structured interview are presented in Appendix A.

  Two kinds of semi-structured interviews are conducted. The first kind involves experts from organisations engaged in the deployment and operation of micro-grids. The participants are selected using purposive sampling, which refers to intentionally selecting participants based on their characteristics, knowledge and experiences [37]. The second kind consisted of semi-structured interviews with community members from various communities, including, community chiefs, community agents, and other users: households, businesses, and community health centres. This information is crucial, as the community members experience the micro-grids firsthand. The community members are selected using convenience sampling, a method of recruiting members based on their availability, willingness, and ease of contact [37]. Due to time constraints not everyone in a community is interviewed. Therefore, at least one interview with a community chief is conducted, as well as interviews with households or businesses to get a complete picture of the community.

  For privacy reasons, all interviewees are anonymous. For this case study in Sierra Leone, 22 interviews are conducted. The interview summaries are presented in Appendix A. These interviews are stated in the text as [38], [39], [40].

A overview of the methods and tools is given below, Figure 2.1.

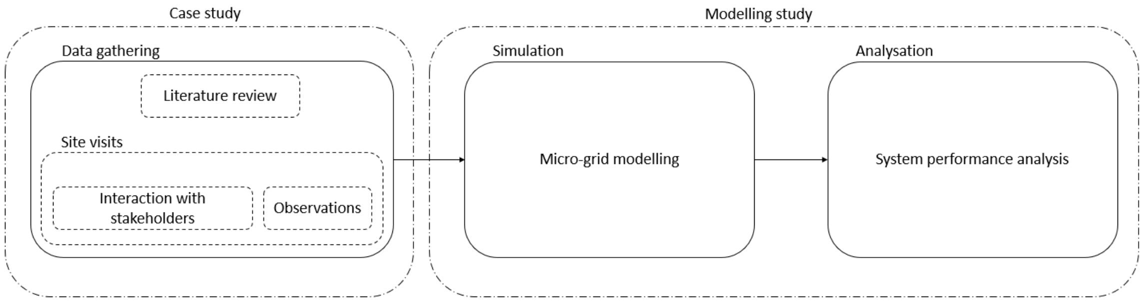


Figure 2.1: Method overview

2.1.2. Simulation tool

In this research, the problem is related to micro-grids and it is about the simulation of existing micro-grids to analyse its performance. Therefore, a power system modelling tool is most suitable for the development of a simulation model to answer the quantitative part of the research. Prina et al. [41] consider five characteristics as important criteria for the selection of an energy system modelling tool: Energy Sector Coverage, Geographical Coverage, Time Resolution, Methodology and Programming Technique.

- *Energy Sector Coverage*:
  A model can concentrate on one specific sector of the energy system or include all sectors. In this research, the model concentrates on one specific sector of the energy system: the electricity sector in terms of micro-grids.
- *Geographical Coverage*:
  Modelling can be divided into single-node and multi-node approaches. A multi-node energy system model considers constraints in the transport of electricity, where the constraints are generated by transmission and distribution limits. A single-node energy system has no constraints in the transport of energy. In this case, the multi-node approach is used as the problem is related to a small electricity grid. To ensure a more accurate model the physics of the power flows are important and cannot be neglected.
- *Time Resolution*:
  A distinction is made between short-term, mid-term and long-term models. Long-term models are used for whole transition periods of a few years. This is not the case in this research so short-term models are the most convenient in this case.
- *Methodology*:
  The methodology can be classified into simulation and optimisation models. In this study, a simulation model is chosen. This is to fill the defined gap in the literature since most of the literature focuses on optimising rural micro-grids in terms of cost and performance. This research is about the performance analyses of deployed micro-grids under different circumstances.
- *Programming Technique*:
  A dynamic modelling technique is used for simulating the micro-grid. Dynamic models capture the time-varying behavior of the system. The performance of the micro-grid is time-dependent and changes dynamically based on factors such as supply and demand for a certain time.

Several modelling tools have been identified that meet the above criteria [41], [42]. These include Python for Power System Analysis (PyPSA) [42] and PLEXOS [43]. PyPSA is an open source and provides a powerful software toolbox for modelling and analysing electrical networks and other forms of energy infrastructure. PLEXOS is a commercial software tool used to simulate electricity markets and optimise energy production and distribution [43]. In the course of the literature review, it became evident that Zebra et al., Bukari et al., Sankoh et al. and Odou et al. all made use of the HOMER software to calculate the optimal grid configuration [25], [26], [18], [17]. HOMER is a widely used modelling tool in the literature, particularly developed for micro-power systems modelling. It is mainly designed to optimise and less for analysing performance [44].

In the end PyPSA is chosen as the modelling tool for this project. PyPSA is a library package from Python. Implementation of a core algorithm in Python is compact and computationally efficient, making it a powerful choice for a wide range of research applications. Vogt et al. discuss the use of Python for data analysis in the field of networks [45]. Complex energy infrastructure projects can be modelled, analysed and optimised. PyPSA has also been used to simulate the German power system [46]. PyPSA simulates and optimises power systems focusing on the physics of the power flows over multiple periods. PyPSA considers Kirchhoff's laws, Ohm's law, and the power flow equations, as part of the power flow calculations performed by the library. Lastly, PyPSA has several functions available for plotting networks. In this way, it can represent and visualise the network for easy understanding. Besides that, the choice is made due to its open-source software toolbox, which allows for its use without a licence. Due to this PyPSA is distinguished by its rich documentation and the existence of a large user community that facilitates its use and dissemination.

3 The case study

This chapter explains the micro-grid system. The micro-grid system is based on a case study in sierra leone. Based on this case study, conclusions can be drawn about micro-grids in rural developing areas. The focus areas are defined in terms of geographic location, technology, appliances and functionality. This all together gives a comprehensive description of the static context in which the system operates.

3.1. Geographic information

The case study is conducted in Sierra Leone, a country with a very low rural electrification rate and one of the locations where development studies are frequently undertaken due to its status as a highly underdeveloped country [7]. To increase the access to electricity, the United Nations Office of Project Services (UNOPS) is assisting the Sierra Leone government through the Rural Renewable Energy Project (RREP). This project aims to design and build solar micro-grids in 97 communities. Figure 3.1 shows the micro-grid communities involved in the RREP projects. The communities selected for the project all contain at least one Community Health Centre (CHC), a prerequisite for the potential construction of a micro-grid.

This case study focuses on four small communities of the RREP. The scope of the research is limited to these four communities due to time and cost constraints. The communities for this case study are selected based on different levels of satisfaction with the general operation and performance of the grid, varying sizes of solar capacity, and logistical feasibility [47]. The 4 visited micro-grids are highlighted in Figure 3.1, named Masiaka, Mathior Line, Medina, and Sendugu. For resident and technical information see Table 3.1. The selected communities are primarily composed of farmer households, with daily activities in agriculture.

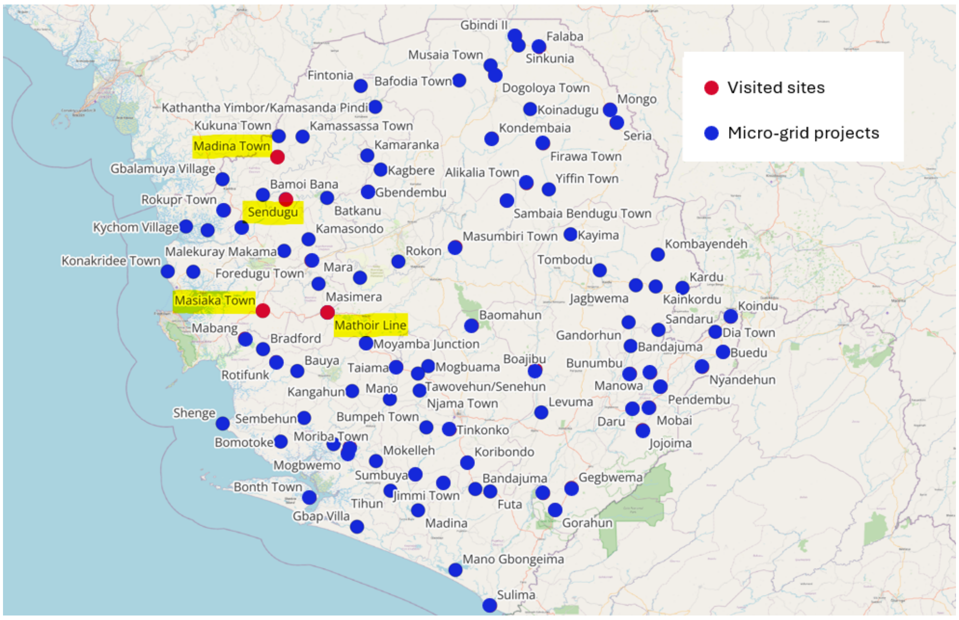


Figure 3.1: Micro-grid projects in Sierra Leone

Community	Province	Inhabitants	Households	Commercial	CHC	Total Connections	kWp generation	Storage kWh
1. Mathior	Tonkolili	2990	-	-	-	208	57	96
2. Masiaka	Port Loko	5630	202	65	1	468	110	720
3. Sendugu	Port Loko	843	48	9	1	58	16	72
4. Madina Junction	Kambia	7609	205	45	1	251	88	434

Table 3.1: Resident and technical information

3.2. The technology

There are different types of off-grid micro-grids. The difference between these types of micro-grids are in the type of generation, storage and distribution components. The site visits contribute to obtaining specific configuration and technical information regarding micro-grids in Sierra Leone.

The communities in this study considers off-grid solar micro-grids with a Alternating Current network [38]. Alternating Current, Direct Current (DC) or hybrid micro-grids exist. DC micro-grids are more efficient when the generation component consist of renewable energy sources, but AC micro-grids are more mature and many devices are set to AC.

Figure 3.2 shows the conceptualisation of the micro-grids in the case study. The generation, storage and distribution components for micro-grids in this case study are summarised below:

- **The generation component**
  The generation components is this case study are solar panels, used for the generation of electricity. This can be categorised as non-dispatchable generation, which means that the generation output can not be easily controlled. Some case studied micro-grids have diesel generators, but are all out of service due to high energy costs [38].
- **The storage component**
  The generation components in this case study are lead-carbon batteries, each with a capacity of 2 kWh. It is a battery system with interconnected lead-carbon batteries. These batteries are used due to low costs [39]. The batteries play a crucial role in enhancing the stability of micro-grids by mitigating the effects of power intermittency. The batteries store electrical energy and convert it back into electricity when demand is low. In two micro-grids the batteries are installed in a 37 m^2 container without windows. In the other two communities, the batteries are installed in a concrete shelter. The batteries are used to control the non-dispatchable output and provide backup power

for the system. Electricity is supplied directly into the grid, and only the surplus is stored in the batteries [38].

- **The distribution components**
  - **The transmission lines**
    Micro-grids can consist of higher voltage and lower voltage transmission lines. Transmitting higher voltages can reduce transmission losses, over long distances. A lower voltage comes out of the socket. The connected appliances often contain a converter to further reduce the input voltage to a level that is safe and efficient for appliances to operate [48]. One of the researched communities exhibits two distinct voltage levels, while the remaining three communities have a single voltage level of 230 volts. At this voltage level a single-phase system is commonly used [38].
  - **The inverter**
    AC micro-grids contain inverters. The primary function of an inverter is to convert DC power produced by solar panels and batteries to AC power, which is the standard form of electricity used to power most household appliances [49], [50]. All the communities have inverters as they are all AC micro-grids.
  - **The transformers**
    A transformer changes the voltage level of AC electricity. It increase the voltage level for transmission over long distances and decrease the voltage for safe use in homes and businesses. Transformers are only required when there are different voltage levels in the transmission lines. This is only the case in one community.

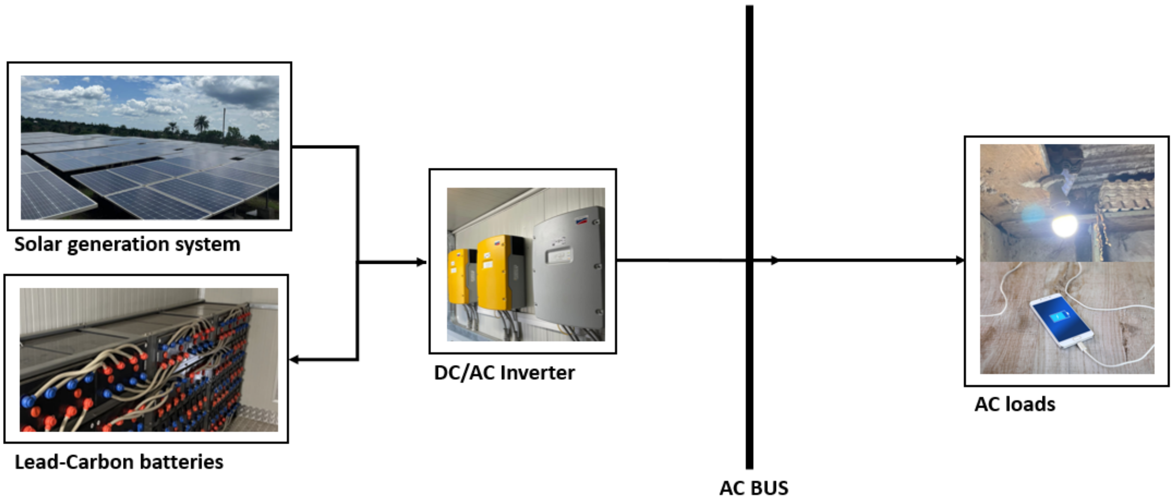
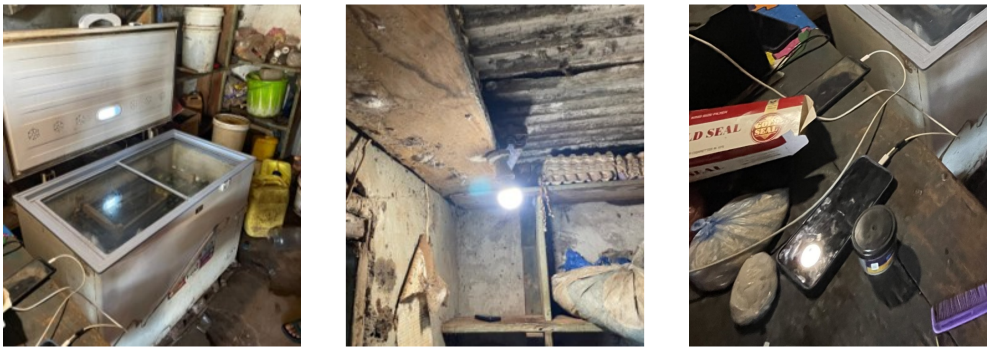


Figure 3.2: Micro-grid conceptualisation

3.3. Appliances

Micro-grids in Sierra Leone are primarily deployed to provide electricity to Community Health Centers (CHCs) and enable households and businesses to connect. This research assumes that each community contains at least one CHC, as the RREP project prioritises the deployment of micro-grids in communities with CHCs. The communities studied predominantly use electricity for human needs, including lighting, entertainment and communication [51]. The most common appliances to use electricity within these communities are mobile phone chargers, lights, freezers, and radios [47], [38]. During the site visits, observations and interviews validated the usage of these appliances.Figure 3.3 shows different appliances during the site visits.



(a) Observation freezer in use **(b)** Observation working light **(c)** Observation phones charging

Figure 3.3: Observations of appliance usage during field research

3.4. Systems functionality

The micro-grid systems operate on a pre-paid basis, where users purchase top-up credits before accessing electricity. The purchased credits are entered into a meter, which regulates the consumption of electricity. The rate at which credits are consumed depends on the household's electricity usage, which varies according to the number and type of appliances in use. Many users complain about the high cost of using the micro-grid [38]. The cost of electricity from micro-grids in Sierra Leone is approximately 0.82 USD per kWh, this is high compared to electricity from the main grid [52], [53].

An average household in a rural developing context consumes about 0.2 kWh of electricity daily, typically using it for at least four hours per day [54]. This corresponds to an average daily electricity cost of 0.164 USD [54]. Notably, 26.5% of the population in Sierra Leone lives on less than 2.15 USD per day, primarily in rural areas [55]. Consequently, electricity costs represent about 8% of the daily income for these users. By comparison, the total energy costs in Europe, including electricity and gas, are around 8% of household income [56]. This highlights the high cost of electricity in Sierra Leone, which makes it financially difficult or even impossible for many households to afford a connect to the micro-grid system.

4 The dynamic context

Micro-grids in Sierra Leone operate within a dynamic context, where a range of actors interact within the system. The involvement of these actors within the technical system creates a socio-technological environment. To understand the dynamic context in which the current system operates, an actor analysis is conducted. This analysis can be found in Appendix B. This chapter is based on the actor analysis provides the actor situation including the actors area of interest, specific objectives and the relations relative to others. Later in this chapter the Key Performance Indicators (KPIs) and system requirements are defined.

The actor analysis is based on both literature and site visits, to collect specific data. The outcomes of the actor analysis depend on the particular case. The data collected through field research is done with site visits in the considered communities. The site visits included interactions with stakeholders as mentioned in subsection 2.1.1. For this case study in Sierra Leone interviews are conducted within the communities and experts. In addition, the site visits and literature results serves as input for defining Key Performance Indicators and system requirements.

4.1. Actor situation

In 2011, the government of Sierra Leone reformed the electricity sector through unbundling of this sector. The National Electricity Act (NEA) and the Electricity and Water Regulatory Commission Act (EWRCA) serve as the primary legislative framework that regulates and coordinates the reformed energy sector. These acts enabled the creation of independent power producers and entities for distribution and generation. It introduced the Electricity Distribution and Supply Authority (EDSA), which is primarily responsible for electricity distribution. Additionally, the Electricity Generation and Transmission Company (EGCT) is responsible for electricity generation. Lastly, the Sierra Leone Electricity and Water Regulatory Commission (EWRC) oversee the sector and ensure compliance with standards and regulations [57].

The ministry of energy

The Ministry of Energy is the policy authority. It is responsible for formulating and implementing policies and regulations for the energy sector in Sierra Leone. It developed energy sector road maps with an implementation plan of national policies, including rural electrification. In addition, it provides oversight functions across the entire energy supply chain for all sector agencies which include the EGTC, EDSA and EWRC [57]. The overall objective of the Ministry of Energy is to produce and distribute sufficient energy from renewable and clean sources. In addition, to improve access for the majority of the population while ensuring a stable and affordable energy supply, with a small focus on rural areas to improve electricity supply in rural communities [6].

Energy and Water Regulatory Commission

The Sierra Leone Electricity and Water Regulatory Commission (EWRC) is an independent regulation authority and regulates the utility service providers in the electricity and water sectors following government laws, acts and policies. The EWRC promote rural electrification and establishes specific micro-grid regulations. These regulations streamlined requirements for renewable energy projects and aligned energy policies, making the investment climate more attractive for micro-grid initiatives. Besides the regulations the EWRC set end-users tariffs for the electricity [21], [58], [20]. The tariffs for the electricity generated by the micro-grids are based on the financial integrity for operation and maintenance for a grid operator, and ensure affordable electricity for users [59], [40], [39]. Their overall objective is to ensure the reliability of electricity and water supply and to promote consumer interest by creating affordable tariff structures [58].

UNOPS

The United Nations Office of Project Services (UNOPS) is the funding organisation and system designer. It is a non-governmental organisation that provides infrastructure, procurement, and project management services in developing countries to support the achievement of the Sustainable Development Goals. UNOPS invested in 93 micro-grids on specific sites in Sierra Leone in the Rural Renewable Energy Project (RREP). UNOPS implements this project on behalf of Sierra Leone's Ministry of Energy to help expand the access to electricity in rural areas. It designed and implemented distribution assets of the micro-grids. Once the micro-grids are designed and deployed the ownership is handed over to the Ministry of Energy and the system operator. The objective of UNOPS in terms of this project is to provide reliable, clean and affordable electricity to facilitate healthcare facilities and help people in rural Sierra Leone [40].

Micro-grid operator

The licensed micro-grid operators, primarily utilising solar micro-grid generation technology, include Winch Energy SL, Off-Grid Power, Power Leone, and Solar Era Holdings SL. These operators are responsible for the design and the construction of generation assets, operation and maintenance, and management of solar micro-grids in Sierra Leone. The grid operators execute this on behalf of the government. The system operators operate under government authorisation and do not hold a monopoly, as the government has granted licenses to four different operators to operate the deployed micro-grids. The operators collaborate with donors, and investors to implement strategic funding agreements aimed at maintaining and expanding their services in Sierra Leone. Maintaining profitability and covering at least operation and maintenance costs is the main objective. This is to provide affordable, reliable, and scalable electricity to satisfy users from micro-grids to communities in Sierra Leone [60].

Community Agent

The community agent is a local operator. It is a community member assigned to take charge of the micro-grid within the community. They are responsible for the contact between the community and the system operator. In addition, the agent is responsible for carrying out minor operational and maintenance tasks to ensure the functioning of the system [38], [39]. The community agent works under the direction of the operators and reports serious unsolvable issues to the grid operator who can send a technician. The agents do not have the resources, engineering knowledge or authority to influence the system's operations or policies. The objective for the community agent is to maintain an operational system, as a functioning system enhances job security and guarantees their access to electricity [38].

The users

The community members, including households, businesses, and Community Health Centers (CHCs), rely on the micro-grid for their electricity needs, seeking affordable and reliable electricity [3]. These users demonstrate a high level of political awareness, which extends even to remote areas [39] [40]. However, they face financial constraints due to the underdevelopment of Sierra Leone, particularly in rural areas. The availability of electricity has a significant impact on their livelihoods, as it increases their potential to generate income. Evening lighting extends their productive hours, allowing them to conduct activities after dark and enabling businesses to operate longer. Their main desire is electricity in the evening. Living without electricity during the day is acceptable [7],[38].

4.1.1. Ownership model

According to Nyarko et al. four ownershop models exist in off-grid micro-grid [20]. The ownership and relations between the actors of the micro-grids in this case study are explained as a hybrid ownership model [20]. This integrates ownership, generation and distribution, and is shared between government bodies and private firms, while the community organisation remains responsible for daily operations. An overview of the interrelationships and dependencies between actors is given in Figure B.2. The micro-grid is deployed by UNOPS and the system operator in cooperation with the government. After deployment, the ownership is handed over to the government. The government is responsible for the micro-grid regulation. System operators have been appointed by the government to be responsible for the operation of the micro-grids. The micro-grids themselves are on a daily operational basis community-based, meaning that it is managed by a community agent [40], [39]. The advantage of this approach is that the investment costs of the distribution assets do not have to be recouped, as the deployment relies highly on funds from UNOPS, which makes UNOPS powerful [20]. The division of ownership and operation leads compared to the other models to high technical and managerial barriers, as many different levels of community exist leading to a complex socio-technical challenge [20].

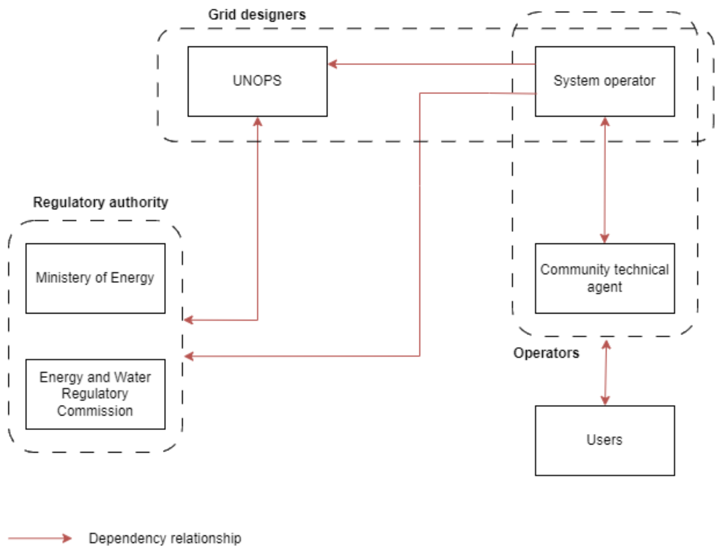


Figure 4.1: Outline of organisational structure and actor dependencies for solar micro-grids in Sierra Leone.

4.2. Key Performance Indicators - Electricity availability

Key Performance Indicators (KPIs) and system requirements emerge from both literature and site visits. The Multi-Tier Framework is commonly used in the literature to define KPIs for micro-grids. This framework outlines performance parameters for the operation of micro-grids, providing a structure to harmonise efforts in improving access to electricity [54]. One of the Sustainable Development Goals aims to ensure access to affordable, reliable, sustainable, and modern energy for all [1]. Terms such as affordable, reliable, and sustainable are further elaborated in the Multi-Tier Framework. As shown in Figure 4.2, the Multi-Tier Framework consists of six tiers (0-5), each representing different levels of energy consumption per electricity connection. This allows for the classification of micro-grids and the KPIs with requirements associated with them.

Based on field research, KPIs from the Multi-Tier Framework are selected. Previous research by Wageningen University found that satisfaction with grid performance was high in communities of Madina and Mathior Line, but lower in Sendugu and Masiaka Town [47]. The field research in this study validates these findings, as users express dissatisfaction with the electricity provided by the micro-grid. The field research shows that 45% of users report load management conflicts leading to electricity outage. Business owners explain that these outage prevent the continuous operation of freezers, affecting the quality of stored goods, which in turn impacts their income [38]. The connected Community Health Centers (CHCs) report that with the advent of electricity, progress has been made, allowing vaccines to be refrigerated and medical treatments to be safer in the evening because of lights [38]. In addition, 50% of respondents complain about insufficient electricity during the evening. The importance of evening electricity access is highlighted through examples from interviews during the field research:

Evening electricity allows my children to study for school at night. - Micro-grid user 1
Evening electricity enables me to work longer and makes it able to cook after dark. - Micro-grid user 2

These findings contradict users' expectations for reliable and affordable electricity, as seen in section 4.1. A well-functioning micro-grid keeps users satisfied and can increase their willingness to pay [25]. This is essential for achieving the grid operator's profitability goal as outlined in section 4.1.

In conclusion, users consider the availability of electricity as important. In addition, this is one of the performance indicators in the multi-tier framework. Therefore, in this research, the average number of hours electricity is unavailable is selected as the main KPI. The electricity is considered as unavailable when the demand is not met during a specified period. In this study, the average number of hours electricity is unavailable is measured in the Loss of Load Expectation (LOLE) hours. The LOLE is commonly used in micro-grid performance studies [61] , [62], [31].

The multi-tier framework includes additional indicators to measure the performance of micro-grids, such as reliability and affordability in terms of costs. Availability is chosen because it aligns more closely with the insights from the case study described above. Additionally, availability provides a more direct and quantitative understanding of the electricity available from the micro-grids compared to reliability, which measures the number of disruptions. Frequent disruptions or long periods of disruptions lead to lower availability. Affordability is not considered in this analysis because the government sets the tariffs and the fact that good performance increases the willingness to pay. Operating below these fixed tariffs would be advantageous, but it is challenging to achieve. This is because the cost of consumption is 8% of household income, which is already considered too high according to the framework [54].

4.3. System requirements

Now that the main KPI is established, the threshold for acceptable micro-grid performance regarding electricity availability needs to be determined. System requirements can serve as boundaries, defining the limit at which the LOLE hours become unacceptable for the micro-grid's performance. This is defined according to the Multi-Tier Framework, which provides specific performance criteria.

In this research, households, businesses and CHCs are connected to the micro-grid. According to the Multi-Tier framework, these connections meet the system requirements of a Tier 4 system as the micro-grid must meet the system requirements related to the highest connection [54]. The CHC connection involves high-load appliances such as freezers, requiring a daily power capacity related to Tier 4 [51], [54]. Tier 4 specifies electricity requirements as a minimum of 16 hours of electricity per day, including at least 4 hours in the evening [54]. For consistency with the KPI, these requirements are expressed in LOLE hours. When these limits are reached, the grid's performance is unacceptable. The system requirements for the micro-grid are as follows:

- **Day requirement:** A maximum of 8 LOLE hours during the day (07:00 - 07:00)
- **Night requirement:** A maximum of 8 LOLE hours at night (19:00 to 07:00).

During the site visits users highlighted that evening electricity is the most desired requirement, as it extends their productive hours [38], [8], [7]. Therefore, electricity during dark hours is more critical than during the day, making the night requirement the highest priority when trade-offs need to be considered.

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Affordability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

Figure 4.2: Multi-Tier Framework for Measuring Access to electricity supply [54]

5

Factors in literature

This chapter identifies and classifies factors in the literature that can influence the electricity availability of micro-grids in rural areas and provides an overview. This is an extension of the literature review conducted in chapter 1, section 1.1.

5.1. Socio-technical review

Despite their promising impact, micro-grids in rural areas face performance challenges. This research involves a comprehensive review of the existing literature on factors that influence the electricity availability of micro-grids in rural areas. Literature indicates that the electricity availability of a micro-grid system is influenced not only by technical factors but also by social, institutional, and economic factors. A socio-technical perspective is chosen for the development of the list of factors. Economic and institutional factors vary notably between countries, which is why these factors are not included in this list. However, it is important to take these institutional and economic factors into account. In chapter 4, the economic and institutional environment in which the micro-grid operates is taken into account.

Factors are selected on the basis of articles relating to the design and operation phase, technical and social aspects, and on the basis of frequency of occurrence in the articles. Furthermore, it is not necessary to adopt specific literature search and selection guidelines, as the number of studies on this topic is limited. An overview of these factors, along with the supporting literature, is presented in Table 5.1.

5.2. Social factors

5.2.1. Community behaviour

The literature stated that community behaviour influences the performance of the micro-grids. Micro-grids experience more performance issues when unfavourable user behaviour occurs leading to:

- **High use of appliances**
  The introduction of electricity leads to the use of more high-load devices, which is logical, but this factor causes overloading of the system if the increase in device usage is not taken into account. This negatively affects the micro-grid performance [25],[16], [28], [63], [64], [27], [65].
- **Inappropriate system use**
  Lack of knowledge and awareness can lead to improper use of the system, people do not know that it is recommended to unplug appliances when leaving the house to save electricity and money. In addition, it can lead to accidental human intervention with critical components, think of the use of transmission lines as clotheslines [16], [27], [28], [63], [64], [65].
- **Connection increase**
  The introduction of electricity can lead to an increase in the number of connections. This may be due to the fact that communities continue to grow and those with a wait-and-see attitude later realise the need for an electricity connection. If the design does not take the future into account,

this can lead to problems. As the community grows, the total load and the distance between houses and the solar and battery system increases. Expanding the micro-grids results in long transmission lines. The longer the transmission line, the larger the losses that occur over the lines. Leading to high electricity losses and load mismatch [28], [64].

5.2.2. Ownership model

- **No sense of responsibility**
  After international organisations and development partners provide grants, technical assistance and project implementation, the ownership is usually transferred to the government or a private company. Poorly defined responsibilities can lead to a lack of ownership, where actors may not feel responsible for the operation and maintenance of the micro-grids, leading to failures [63], [25].

5.2.3. System security

The level of system security can affect the performance of micro-grids:

- **Illegal power drain**
  Community members who use up their paid credits can use prohibited ways to drain power, research shows. This kind of behaviour can create performance issues [28], [16], [63].
- **Component theft**
  Theft of components is also a problem in deployed micro-grids. The literature stated that critical components, such as distribution boxes or energy meters can be stolen leading to performance issues of the micro-grids [16], [63].

5.3. Technical factors

5.3.1. System design

- **Low system design quality**
  As micro-grids are implemented in low economic areas, this often leads to the use of low-quality components, resulting in frequent component failures. The literature identifies several system quality issues related to low-quality components, which can cause failures and unexpected power losses due to inefficiencies in electrical components as the solar generation system, battery system and distribution system with transmission lines and poles [26],[16], [66], [64], [65], [29], [63], [27], [10].
- **Inappropriate system design**
  A lot of micro-grids in rural areas are designed by experts from international organisations who are not familiar with local conditions, leading to micro-grids that do not fit the local context. This can lead to inappropriate system design. For example, neglecting protection materials from lightning results in frequent lightning strikes, which damage the grid. Grounding is crucial for micro-grid safety, preventing overvoltages and safely discharging electric currents during faults or short circuits. Without grounding, transmission lines, equipment, and components risk overheating [29], [16], [65].
- **Insufficient system capacity**
  The literature identifies numerous capacity-related issues. Many micro-grids experience mismatches between system design and actual demand. This can be attributed to misunderstandings by the community regarding developers' questions about appliance usage. The inaccurate capacity design causes mismatch between supply and demand, which negatively impact grid performance [25], [26], [66], [28], [16], [67], [14], [10].

5.3.2. System operation and maintenance

As the local agent is the first point of contact in a community regarding any issues with the micro-grid, the knowledge of the local agent is a crucial factor. Existing literature indicates that a lack of knowledge among agents fosters performance issues.

- **Lack of qualified technicians**
  The absence of qualified technicians in the community to manage the systems and repair dam-

aged components can result in long repair times. Since the community agent lacks technical expertise, a qualified technician must travel to the sometimes far and hard-to-reach rural community [28], [64], [66], [63], [67], [14].

- **Lack of operation and maintenance procedures**
  A lack of trained community agents can lead to the absence of maintenance tasks. Community agents do not understand the need for maintenance, resulting in maintenance routines being performed less frequently. For example, this can lead to dusty solar panels that are not routinely cleaned, or batteries that overheat when it is not known that they should be turned off at high temperatures [67],[29],[63], [10].

5.3.3. Exceptional events

- **Extreme weather conditions**
  Extreme weather conditions like heavy rains, extreme temperatures, and lightning can affect the performance of the grid [16], [66], [10].

From Table 5.1, it emerges that high use of appliances, inappropriate system use, low system design quality, insufficient system capacity and lack of technicians are the most frequently mentioned in the reviewed literature.

Social factors		
Community behavior		
	High use of appliances	[16], [25], [27], [28], [63], [64], [65]
	Inappropriate system use	[16], [27], [28], [63], [64], [65]
	Connection increase	[28], [64]
Ownership model		
	No sens of Ownership	[25], [63]
System security		
	Illegal power drain	[16], [28], [63]
	Component theft	[16], [63]

Technical factors		
System design		
	Low system design quality	[10], [16], [26], [27], [29], [63], [64], [65], [66]
	Inappropriate system design	[16], [29], [65]
	Insufficient system capacity	[10], [14],[16], [25], [26], [28], [66], [67]
Local technicians		
	Lack of technicians	[14], [28], [63], [64], [66], [67]
	Lack of operation and maintenance procedures	[10], [29], [63], [67]
Exceptional events		
	Extreme weather conditions	[10], [16], [66]

Table 5.1: Factors influencing the performance of micro-grids in rural developing areas

6

Factor validation from field research

The last chapter identifies potential factors affecting the performance of micro-grids through a literature study. This chapter validates these factors through the case study with site visits of four micro-grids in Sierra Leone. These site visits involve observations and interactions with stakeholders, corresponding to the research approach. Interactions with stakeholders are conducted through semi-structured interviews. After validation, the frequency of occurrence for each factor is determined. Consequently, the most relevant factor is identified.

6.1. Factor validation

This case study examines the four communities of Mathior, Maskiaka, Sendugu, and Madina. The identified factors are checked in all four communities to validate them. The semi-structured within the community and experts interviews and the direct observations combined, strengthen the accuracy of the factor validation. An overview of the factors and their validation can be found in Table 6.1

Social factors		N communities	N experts	N observations
Community behaviour				
	High use of appliances	4	2	1
	Inappropriate system use	3	0	1
	Connection increase	4	0	0
Ownership model				
	No sense of ownership	1	2	0
System security				
	Illegal power drain	1	0	0
	Component theft	1	0	0
Technical				
System design				
	Low system design quality			
	Batteries	4	2	3
	Transmission lines	3	0	2
	Poles	2	0	2
	Inappropriate system design	3	0	2
	Insufficient system capacity	3	0	0
Local technicians				
	Lack of technicians	4	1	0
	Lack of maintanance and operations procedures	2	2	1
Exceptional events				
	Extreme weather conditions	2	1	0

Table 6.1: Frequency of occurrence of factors influencing the performance of micro-grids in rural developing areas

6.1.1. Micro-grids validation insights from site visits

Table 6.1 is based on the site visits. The main insights found for the factor validation are mentioned in this subsection.

Interaction with stakeholders

- The interviews consistently highlighted the fact that batteries suffer from failure issues and deal with short lifespans, leading to performance problems in the evening. Both experts and almost all community members reported this problem, and non-functioning batteries were observed in 3 of the researched micro-grids. Most of the time, electricity is available for a maximum of one hour after dark, leaving community members dissatisfied.
- Site visits revealed that the high use of appliances led to load management conflicts within the grids. It appears that freezers consume a significant amount of electricity, the day before market days posed a significant challenge, with frequent grid outage occurring due to increased demand for cooling products using freezers. In all four communities high use of appliances leading to grid blackouts it detected. This leads, according to users, to the extent that the batteries cannot recharge during the day, contributing to the lack of electricity in the evenings.
- The micro-grids have reached their maximum number of connections in terms of capacity, it is not possible to connect any more community members.
- The lack of highly skilled technicians is a recurring issue in these communities, resulting in long waiting times for major repairs.
- The absence of adequately trained community agents leads to a lack of consistent maintenance and operational procedures. Site visits reveal that maintenance practices vary between communities, ranging from structured procedures to inconsistent daily routines. For example, it was observed that solar panels were cleaned irregularly, which adversely affected their efficiency.
- Extreme weather conditions significantly affect micro-grid performance. Incidents such as thunderstorms, heavy rainfall, and strong winds damage components, cause fires, and in some cases, necessitate grid shutdowns. Additionally, extreme heat increases the risk of battery overheating.

Observation

Various factors were observed during the site visits that can, if applicable, cross-validate the factors mentioned in the interviews. Some observations are shown see Figure 6.1, the full list of observed factors is presented in Table 6.1. Figure 6.1a shows consequences of fire in micro-grid due to extreme weather conditions [38], Figure 6.1b show the consequences of a lack of maintenance procedures and Figure 6.1c show the consequences of low-quality grid-design leading to a broken pole.

(a) Observation inappropriate design: Evidence of fire in micro-grid

(b) Observation Lack of maintenance: Dusty solar panels

(c) Observation Design quality: Broken pole

Figure 6.1: Observations during field research

6.2. Identification relevant factors

The most relevant factors are determined based on the frequency of occurrence within the community and mentioned in an expert interview. Therefore the factors most validated in communities and identified by an expert, are considered relevant. The semi-structured interviews with experts are included, as these individuals are closely involved in the development or operation of the micro-grids and possess extensive knowledge. If a factor is mentioned by one expert, it is considered sufficient. The frequency of occurrence of the factors mentioned across expert interviews is not taken into account, as not all experts have information on every factor. This approach is based on the research of Numminen et al., where performance problems are ranked according to the number of times the problem is reported [16]. In the literature review chapter 5, these factors were also frequently mentioned, confirming these findings. The most relevant factors are:

- High use of appliances
- The low design quality of batteries
- Lack of technicians

6.2.1. Sensitivity analysis identification relevant factors

Based on the frequency of occurrence in community members and expert interviews, relevant factors are selected. In this case, the frequency of occurrence and expert interviews are combined. An alternative approach could have been to focus solely on the frequency of occurrence in the communities and have it validated through expert interviews. This approach would have identified four relevant factors, but the factor ”Connection increase” is not validated in the interviews, and would thus be excluded, leaving the same three relevant factors. This demonstrates that this approach is not sensitive and does not affect the relevant factor selection of this case study.

6.3. The most relevant factor

Out of the relevant factors one most relevant factor is chosen. The quantitative impact of all factors is not explored, due to time constraints. The most relevant factor is chosen based on the KPI formulated in section 4.2, the average number of hours electricity is unavailable.

The most relevant factor in this research is the quality of batteries. In this research, the impact of the quality of the batteries in terms of battery performance is analysed in the model study. This is because the battery performance has a direct impact on the electricity availability in the evening on all solar-powered micro-grid systems. A requirement of the system performance is mentioned in section 4.2. A solar-based micro-grid without batteries or backup generators can not meet the system requirement of evening electricity. The battery is therefore a critical infrastructure component within the micro-grid. This is not the case for the lack of technicians. The lack of technicians can lead to a decline in electricity availability over time, it does not always have the same direct impact on electricity availability as battery performance has. The same applies for the high appliance usage, which does not have a direct impact on electricity availability in the first place. This is because high appliance usage is possible in micro-grids with a lot of available capacity. Therefore battery performance is the most relevant factor in this study.

The most relevant factor is based on its impact on the requirement for electricity availability in the evening. If another criterion, such as impact on revenue or ease of mitigation, is selected, it would lead to different results. However, this was not identified as the most important requirement in this research and is therefore not applicable.

6.4. Key Performance Indicator - Lifetime of the battery

Since the most relevant factor in this research is the battery performance, the battery lifetime is also included as a KPI. The battery performance declines over time. As the number of cycles increases, defined as one full charge and one discharge, the performance of the battery decreases and so does the rated capacity of the battery. After a certain period, the battery’s performance degrades to the point where it can cause performance issues in the micro-grid [68]. The battery’s lifetime indicates how many days the battery will operate, assuming one cycle per day. When the battery performance level impacts the system to such an extent that the micro-grid no longer performs within the system requirements, it is recommended to replace the batteries.

The lifetime of batteries is represented using a fade curve, which is crucial for understanding battery degradation and performance over time. This allows the battery's lifetime to be determined in this study. Figure 6.2 shows the fade curve used in this research, which represents the normalised battery capacity as a function of the number of cycles. This curve, along with the LOLE hours at each battery performance level, serves as an input for determining the battery's lifetime at different performance levels.

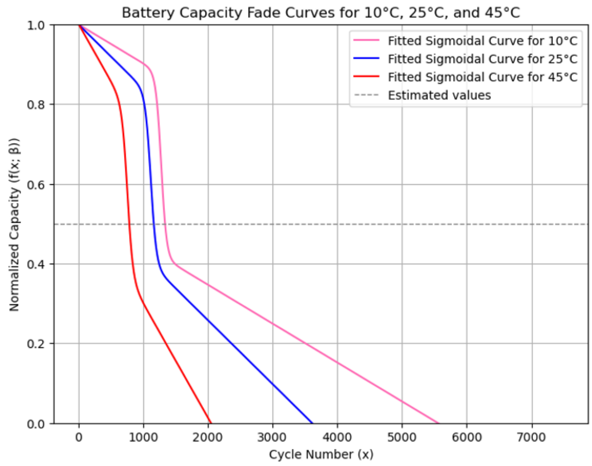


Figure 6.2: The capacity fade curve under different temperatures used [68]

The fade curve is derived by the extrapolation of an existing fade curve using the methodology outlined in section D.4 [68]. Current local conditions assume the battery is exposed to high temperatures due to the high climate temperatures and internal heat generation within the battery house [69]. It is therefore assumed that the battery is exposed to a temperature of around 45°C and this curve is used in the base model. Interviews with the grid operator indicate that lead-carbon batteries have only half their estimated lifespan, operating for approximately five years under current conditions, which corresponds to the estimated number of cycles in Figure 6.2 [38]. So the 45°C curve aligns with actual battery performance in the case study.

Lithium-ion cell fade characteristics are chosen due to the availability of data. Notably, lithium-ion batteries generally have twice the lifetime of lead-carbon batteries [70]. While this difference should be considered when evaluating battery performance in micro-grids, it does not affect the comparative analysis between the strategies in this research since the same curve is applied across all cases.

In conclusion, the two KPI used in this research are:

- The average number of hours electricity is unavailable in LOLE hours.
- The lifetime of the battery in cycles.

7

Mitigation strategies

In this research, battery performance is identified as the most relevant factor in chapter 6, serving as a key input for developing mitigation strategies. Additionally, it is essential to define the solution space to ensure that the strategies are suitable for the rural developing context, as outlined in this chapter. Following this, the identified mitigation strategies are explored, each representing a unique strategy to reduce the impact of the battery performance on the electricity availability in micro-grids.

7.1. The mitigation solution space

The actor analysis outlines the context in which the micro-grid system operates. The actor situation and relationships between stakeholders based on literature and site visits outline the scope of the solution space, to find mitigation strategies for the micro-grid electricity availability problems caused by the battery performance. The constraints within the mitigation strategies need to fit are mentioned in this subsection. Appendix B provides a comprehensive explanation of the actor analyses.

- **Regulatory environment:**
  The power-interest relation between the grid operator and the Ministry of Energy and EWRC is currently locked. They are responsible for the micro-grid regulations. The EWRC is not open to new tariff negotiations, as both they and the Ministry of Energy prioritise maintaining public support, given that the population already considers the existing tariffs too high [39], [38]. UNOPS asserted that their responsibility is limited to the development of distribution assets, and upon completion of their construction, their ownership is handed over. The grid operators are responsible for generating assets from the beginning. Because of this relationship, the mitigation strategy should be independently implementable by grid operators without governmental support in terms of regulations and support from UNOPS for distribution assets.
- **Technical environment:**
  The mitigation strategies must align with the technical configuration and capabilities available in the community. The grid operators are not always on-site and the community agent has limited technical expertise. The agent is primarily responsible for maintaining components and performing minor repairs [38]. Therefore, the solution must fall within the technical knowledge of the grid operator and especially the knowledge of the community agent. In conclusion, the mitigation strategy must fit within the current knowledge and configuration of the micro-grid system.
- **Economic environment:**
  The actor situation indicates that the Energy and Water Regulatory Commission (EWRC) holds significant authority in tariff regulation of micro-grids. Grid operators rely on the EWRC's tariff regulation. Currently, tariffs are insufficient for system operators to cover maintenance and operations, which affects the performance of the micro-grids [39]. Grid operators waiting for the government to change the regulatory structure or an increase in tariffs. Consequently, mitigation strategies are limited by costs. It is noted that strategies cannot be implemented without incurring some expenses, but the lowest-cost strategies need to be considered.

7.2. Mitigation strategies

In literature, different strategies are explored. These strategies are chosen because of the best alignment with the current environment, considering the system's solution space, including regulatory, technical and economic constraints.

7.2.1. Demand control regulations

Demand control (DC) is identified in the literature as an effective tool for energy management in micro-grids, particularly for improving energy utilization. DC is often combined with storage in the literature to improve the performance of micro-grids [71], [31], [30].

In this context, DC involves rearranging the operation time by shifting the time window in which electricity is provided. During specific hours, the micro-grid disconnects the electricity supply and recharges the batteries with the generated electricity. DC assumes that flexible activities can be shifted to other times. It assumes that load from users, such as charging phones, can be shifted and less adaptable activities, like lighting, which are considered as essential during the night, are then prioritised.

DC is considered a viable solution within the system's constraints. DC can be implemented by grid operators and fits into the current micro-grid configuration without the need for additional components. It is compatible with regulatory and technical frameworks. Economically, there are no additional costs as demand response offers benefits by avoiding the need for additional transmission or generation infrastructure. However, the hours of no electricity impact grid operator revenues. The electricity tariffs in the case study micro-grid are 0.82 USD per kWh, see chapter 3. A 3-hour shutdown during those demand-controlled periods throughout the year results in 46 kWh of missed electricity sales, based on the totale electricity load profile of the community. This amounts to an estimated 38 USD per year in lost revenue.

7.2.2. Implementation of air conditioning

Field research revealed that the batteries are subjected to high temperatures due to the local climate, and the battery houses lack adequate cooling.[38], [39]. In addition, studies indicate that the performance of batteries decreases due to high temperatures, resulting in a shorter lifetime [62], [72], [73], [71]. Batteries in warm, humid, and hot, dry regions face significant degradation rates [62]. Also the fade curve in Figure 6.2 shows the degradation of a lithium-ion cell under different temperatures [68]. Therefore the implementation of air conditioning could be a mitigation strategy for the effect of battery performance on the electricity availability.

This study analyses the addition of air conditioning as a mitigation strategy. Cooling the batteries with air conditioning aligns with the regulatory environment since grid operators can implement this. For the technical environment air conditioning fit in the current configuration of the existing micro-grids. However, air conditioning is not yet integrated into the micro-grid, so new knowledge will need to be acquired. This will be minimal compared to, for example, implementing new types of renewable energy. For the economical environment, the use of air conditioning is cheaper than the increase of solar panels per kW per year, see Appendix C. This is the use of air conditioning without increasing solar panels, thus using the electricity generated by the deployed solar panels. With a lifetime of 15 years, the costs of a 1 kW air conditioning range from approximately 30 to 66 USD per year, though this may vary depending on the specific type [74]. Note that cooling the battery extends its lifetime and can reduce life cycle costs, making the investment more sustainable over time [68], [62], [72].

7.2.3. Battery capacity increase

In system sizing studies the effect of the size of solar panels and battery capacity on the performance is analysed [32], [26], [75], [25]. Zebra et al. show that by increasing the number of batteries the system performance improves. In the study of Benavente et al. shows that an increase in battery capacity prevents the risk of electricity outage while increasing the system performance. An increase in solar generation capacity can lead to a higher battery ageing rate. High SoC levels accelerate ageing, leading to early battery failure, while adding extra storage can help maintain a lower SoC [32], [62]. Mitigation strategies based on increasing the battery or solar capacity are interesting to consider.

Both solar and storage solutions align with the regulatory environment, as both assets are part of the generator assets under the responsibility of the grid operator and no new regulations are needed. From a technical perspective, both strategies fit within the current technical environment. Lead-carbon storage and solar panels are already part of the existing configuration, so there is some level of expertise available. A technical advance is that storage can provide electricity during the evening hours, which is one of the system requirements outlined in section 4.2. This makes the addition of extra storage particularly attractive. From an economic perspective, however, financial resources are required to implement either strategy. If financial resources are available, it can be invested in additional storage or solar panels. When considering the lifespan and capital costs of both technologies, batteries present a more cost-effective option. The capital cost for batteries is 30 USD per kW per year, while for solar panels it is 75 USD per kW per year, see Appendix C for calculations. In addition, the operational costs for batteries are also lower. This makes the investment in batteries more financially attractive. For these reasons, additional storage is analysed as a mitigation strategy in this research.

Other strategies, such as upgrading the quality of components, implementing a combination of storage technologies, adopting hybrid generation configurations or the use of a diesel generator are not considered as they do not fit into the economic and technical environment.

8

The micro-grid model

This chapter describes the construction and development of the micro-grid model. For this research, the micro-grid is represented through a computer model to analyse its performance in terms of electricity availability under different battery performance levels. After developing the general model, it is adapted to the specific case study. This is achieved by defining the model's boundaries and input parameters related to typology, technology, and time frame of the researched micro-grids.

8.1. Conceptualisation of a rural micro-grid system

For the model, a micro-grid model is build based on the four case study micro-grids. The micro-grid consists of components including a solar system, battery system, and distribution system, forming an isolated micro-grid within the remote community. The design of the micro-grid and its electrical characteristics are essential for the system's conceptualisation. The following sections present the conceptualisation of the modelled the system.

8.1.1. Micro-grid components

Micro-grids can be modelled as a network and represented as a graph, a mathematical structure used to model pairwise relations between objects [76]. This involves simplifying georeferenced points and edges, as shown in Figure 8.1. A graph consists of a set of buses and a set of edges, corresponding to transmission lines, which are electrical conductors through which electricity flows. To build the model, each bus can be assigned to a specific component, representing generators, loads, or storage [77]. The following information is declared from PyPSA Documentation [42]. Each component can be assigned specific input values and if technical characteristics are missing, PyPSA uses default values. In PyPSA, the two key components are utilized:

- Lines
  Lines are the theoretical edges in the network. Lines include distribution and transmission lines, overhead lines and cables. Lines already have the main characteristics of transmission lines. They are unidirectional meaning the power flows in one direction. Line elements are represented as resistors in the model and have a maximum line capacity. The length of the lines is important for the reactance. Lines connect a bus to another bus. For implementation characteristics, see Appendix D, subsection D.2.1.
- Buses
  Buses are the theoretical nodes in the network to which components such as loads, generators, and transmission lines are attached. It enforces energy conservation for all elements feeding in and out, in line with Kirchhoff's Current Law. Buses can be modelled as source buses, load buses, or hybrid buses, depending on their capacity to consume or produce energy. The location of buses is defined by coordinates. Different system components can be linked to buses, allowing a simplified representation of a micro-grid by connecting lines and buses.

  Components with specific properties are assigned to lines or buses within the system, including:

- **Generation**
  Generators are attached to a single bus. Generation can be seen as a source bus, feeding electricity into the system. In this research, two generation components are added. Normally, a generator has two controls: active power control and voltage control. However, renewable energy generators do not have these controls and are treated as load buses. This means that the power output is fixed and does not depend on the micro-grid configuration.

  The first source bus consists of solar panels, which are modelled as a constant power bus since it is a renewable energy source. This means that the power injection (P) and voltage (Q) are known, and referred to buses with control system PQ. The power output is defined by the generation profiles of the solar panels throughout the day, as shown in subsection 8.3.2, Figure 8.2. The second generation component is the slack generator, with control system: 'slack'. A slack bus serves as a reference point for the voltage angle, as these are computed relative to a specific value. The real and reactive powers at the slack bus are adjusted to ensure that the rest of the system remains balanced, an electrical requirement. For example, it compensates for system losses [78]. This input is defined by the generation profile, as shown in subsection 8.3.2.
- **Load**
  The load is attached to a single bus, known as load buses, which consume electricity in the system. Load buses have specified values for net active (P) and reactive power (Q) injection and therefore operate under the PQ control system. In this research, the load buses represent households, Community Health Centers (CHCs), and businesses that consume electricity from the network. As this study involves simulation, the load buses are modelled as constant power buses, meaning the power input is fixed. This input is defined by the consumption profile, as shown in subsection 8.3.3.
- **Storage Unit**
  The Storage Unit is connected to a single bus and functions as a hybrid bus, capable of injecting power into or absorbing power from the grid. It inherits its energy carrier from the bus to which it is attached. In this research, the hybrid buses are represented by lead-carbon batteries. The energy levels of the storage units are cyclic, preventing the free use of storage capacity and ensuring that the model does not end with a lower storage level than it starts within the next time step. Lead-carbon batteries are used in the modelled micro-grid. The input variables of the battery are shown in Appendix D, subsection D.2.2. The lead-carbon batteries are 2 kWh each and are interconnected. For simplification, the interconnected batteries are modelled as one battery in the model. Since these batteries are of the same type, situated in the same location, and operating under identical conditions, the differences between the model and reality are expected to be minimal.
- **Inverter**
  Inverters are not a standard component in PyPSA. Instead, a Link component can be used in the model to convert between Alternating Current (AC) and Direct Current (DC) networks. However, only transmission lines are used in the micro-grid to account for transport losses along the lines, meaning that no Links are present. Consequently, the network is assumed to consist solely of AC carriers, and no inverters are implemented. This decision was made due to the lack of available data.
- **Transformers** Transformers are only required when there are different voltage levels in the transmission lines. This is only the case in one community, so no transformers are not included in the model.

8.2. Power Flow Analysis

In system modelling, there are two types of modelling: simulation and optimisation. In this research, a simulation model is created, to analyse the system's behaviour.

A power flow analysis gives an overview of how electrical power is transmitted and distributed from generators to various loads within an electrical power system of interconnected buses and transmission lines. This is to assess the electrical performance of the micro-grids and it is therefore an essential tool for understanding electricity systems, as a power flow analysis considers the properties of electricity and the losses that arise during its transport.

The power flow, also known as load flow, between two nodes over a single conductor is described as the transfer of electrical power. A conductor is a material that allows the conduction of electrical current, due to its low electrical resistance. The voltage differences between the connection points of buses in an electrical conductor permit charged particles to flow between these buses. In a network with multiple lines and buses, the impedance of a conductor is a crucial characteristic. Impedance includes both resistance and reactance, collectively determining the total opposition to current flow in an electrical circuit. The impedance is crucial because the current through a conductor is inversely proportional to its resistance according to Ohm's Law. The actual power flow in a network can be calculated with the Alternating Current method (AC) and approximated with the Direct Current method (DC). In this research, the micro-grids are AC systems. The derivation and calculation in the network are explained in the next sections. In a power flow without optimisation calculation, the dispatch of the system needs to be determined at every time step. When the dispatch of all dispatchable components such as loads, generators, and storage are specified, a power flow analysis is performed.

8.2.1. Power flow equation for AC micro-grids

In a power flow calculation for AC networks, PyPSA uses a non-linear equation which is solved using the Newton-Raphson algorithm, which is automatically taken into account in PyPSA. It performs calculations related to the resulting voltages in the network and to the active and passive power flows f_l in the lines $l \in L$ injected or consumed at each of the buses, $n \in N$. Active power, P_n, at bus $n \in NN$, is the real power, which gives electrical energy. It is always positive and flows from source to load. Reactive power, Q_n, at bus $n \in N$ occurs in AC circuits when voltage and current are not in phase. The reactive power oscillates back and forth between the source and the load, without performing useful work. The symbol i in Equation 8.1 is added to the reactive power to indicate that this part is imaginary. The apparent power, S_n injected at bus $n \in N$, is sum of the complex real and reactive power:

$$S_n = P_n + iQ_n \qquad \forall n \in N \tag{8.1}$$

8.2.2. Constraints

To simulate existing micro-grids constraints of the grid need to be taken into account. The conceptual constraints of the micro-grids need to be translated into mathematical constraints. In PyPSA the equations for constraints are constructed, but a mathematical overview is given below.

Power balances

The power flow in a system is influenced by two principles known as Kirchhoff's Current Law and Kirchhoff's Voltage Law. Kirchhoff's Current Law states that the total current entering a bus is exactly equal to the total current leaving the same bus. In other words, the Current Law requires a closed cycle network and the algebraic sum of the in- and outgoing flows equals zero. Kirchhoff's Current Law is expressed by using the incidence matrix, $K_{n,l} \in \{-1, 0, 1\}$. An incidence matrix is a matrix that symbolically represents the network, the order $|N|$ number of buses and $|L|$ number of lines is $|N| \cdot |L|$. The incidence matrix has non-zero values +1 if line $l \in L$ starts on bus $n \in N$ and −1 if line $l \in L$ ends on bus $n \in N$. To guarantee the physicality of the network flows, in addition to Kirchhoff's Current Law, Kirchhoff's Voltage Law must be enforced in each connected network. Kirchhoff Voltage Law is about the electric potential differences in each closed electricity loop within the micro-grid. It states that the sum of potential differences across lines around the electricity loops in the micro-grid network must sum to zero.

PyPSA balances the inelastic electricity demand, meaning that the inelastic electricity demand $d_{n,t}$ at bus $n \in N$ must be met at each time $t \in T$ by the dispatch of the generators, $g_{n,t}$ and the dispatch of the storage $h_{n,t}$ for $n \in N$ and $t \in T$ or by the power flow $f_{l,t}$ in the lines $l \in L$ at $t \in T$. In any case, the carriers in this research are electricity from solar panels and lead-carbon for the batteries, so they are left out of the equations [42].

$$d_{n,t} = \sum_{n \in N} g_{n,t} + \sum_{n \in N} h_{n,t} + \sum_{l \in L} K_{n,l} f_{l,t} \qquad \forall n \in N, t \in T \tag{8.2}$$

Transmission lines

The absolute power flow $|f_{l,t}|$ through the transmission lines $l \in L$ at time $t \in T$ is constrained by the transmission line capacity F_l for $l \in L$.

$$|f_{l,t}| \leq F_l \qquad \forall l \in L, t \in T \tag{8.3}$$

Storage

The dispatch of the storage depends on its State of Charge (SoC), $e_{n,t}$ in bus $n \in N$ and $t \in T$ which signifies the part of the storage capacity that is available for discharging. The SoC is influenced by both charging, $h_{n,t}^{in}$, and discharging, $h_{n,t}^{out}$, activities at each time step, as well as the SoC from the previous time step. Efficiencies for charging and discharging, are denoted as η_1 and η_2 respectively. It also takes into account the self-discharge of the battery, λ. When considering an AC micro-grid, the battery also takes into account the power loss through the transmission lines, $P_{l,t}^{loss}$, in line $l \in L$ at time $t \in T$. These are calculated in the power flow analysis. The equation for the state of charge is:

$$e_{n,t} = e_{n,t-1} \cdot (1-\lambda) + \eta_1 h_{n,t}^{in} - \eta_2^{-1} h_{n,t}^{out} - \sum_{l \in L} P_{l,t}^{loss} \qquad \forall n \in N, t \in T \tag{8.4}$$

To avoid simultaneous charging and discharging, the SoC must be consistent with the dispatch at all times and is limited by the storage capacity H_n for $n \in N$. Furthermore, the equations below constrain that the SoC cannot exceed the energy capacity of the batteries and cannot be less than zero.

$$0 \leq e_{n,t} \leq H_n \qquad \forall n \in N, t \in T \tag{8.5}$$

$$0 \leq h_{n,t}^{in} \leq H_n \qquad \forall n \in N, t \in T \tag{8.6}$$

$$0 \leq h_{n,t}^{out} \leq H_n \qquad \forall n \in N, t \in T \tag{8.7}$$

8.3. Input data

The model foundation and mathematical equations are now established. Site-specific input data is implemented. Obtaining technical information in developing countries is challenging due to a lack of technical expertise, restraint to share information, and the complexity of international collaborations. Much of the data has been obtained through literature, and more accurate input data could improve the model's performance.

The micro-grid is modelled, based on the four visited communities, see Table 3.1 for their characteristics. For the modelled micro-grid, the 16 kWp system and topology of the community Sendugu are assumed, it reflects the smallest capacity micro-grid observed among the visited communities. Sendugu is selected due to its smaller size in terms of time constraints and the poor performance of the grid. This micro-grid has 58 connections based on the site visit and has a total storage capacity of 72 kWh.

8.3.1. Topological Micro-grid

During field research, the Sendugu grid is mapped using Google Maps with satellite view, drawing the grid to scale and identifying the connected users and transmission lines. This approach is necessary due to the absence of a technical micro-grid map. While feasible for smaller grids, this method becomes time-consuming as grid size increases. Field research revealed that all micro-grids follow a hub-and-spoke design, where a central solar and battery system serves as the main distribution point with several lines extending outward, see the topological of the micro-grid in Figure 8.1. This design facilitates the expansion of micro-grids by extending the transmission lines. After mapping, the connections and lines were converted into coordinates for implementation in the model. The data contains only topological features of the transmission grid, excluding electrical properties.

To verify the accuracy of the drawn grid, the coordinates are plotted and compared with satellite imagery, Figure 8.1. The total distances between the plotted coordinates are calculated and compared with the scaled distances on the Google Maps satellite image, as shown in Appendix D. The coordinates and measured distances matched the actual layout, confirming the accuracy of the mapped grid.

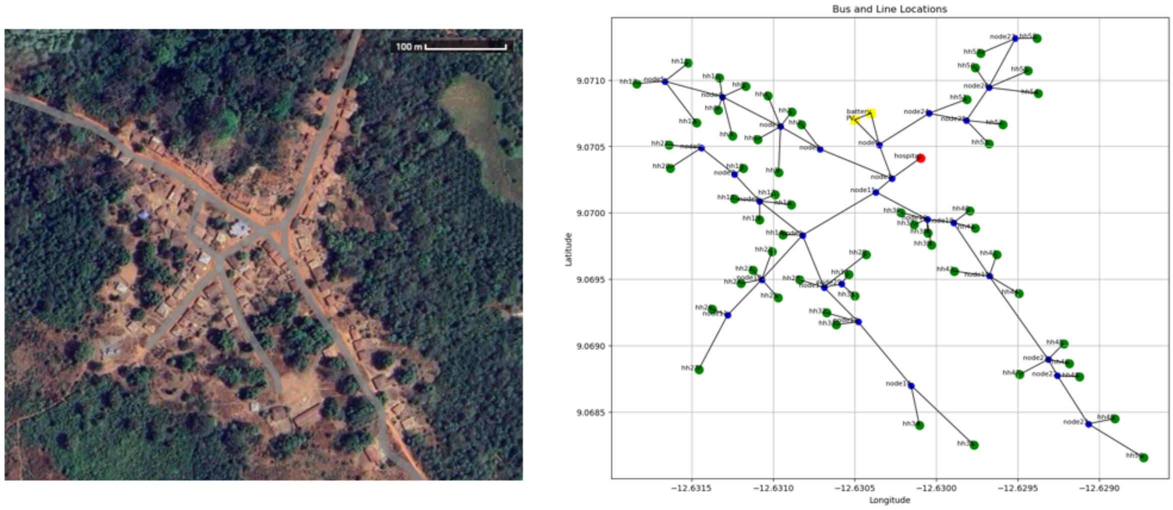


Figure 8.1: Conceptualisation micro-grid

8.3.2. Generation profile

Solar generation is an exogenous input variable in the model, meaning its values are set externally and depend on the input time series in the model. The generation profile is retrieved from Renewables.Ninja. Renewables.Ninja is a tool designed to generate solar energy production profiles based on the NASA MERRA-2 Reanalysis dataset. Reanalysis data is produced using advanced climate forecasting models, offering the significant advantage of providing global data for locations and time points where direct data is unavailable [79], [80].

The dataset features a spatial resolution of 9.14± latitude and -11.89± longitude, along with an hourly temporal resolution. A system loss fraction of 0.1 is used, as this is the default value. However, this depends on the type of solar panel used. The solar panels used have a capacity factor of 1.5 [79], [80]. The generation profile is based on the solar irradiation at a specific time step and the installed capacities. A generation profile for a 1 kWp system is provided, based on the radiation profile from 2019. This profile is scaled up to simulate a grid with a capacity of 16 kWp.

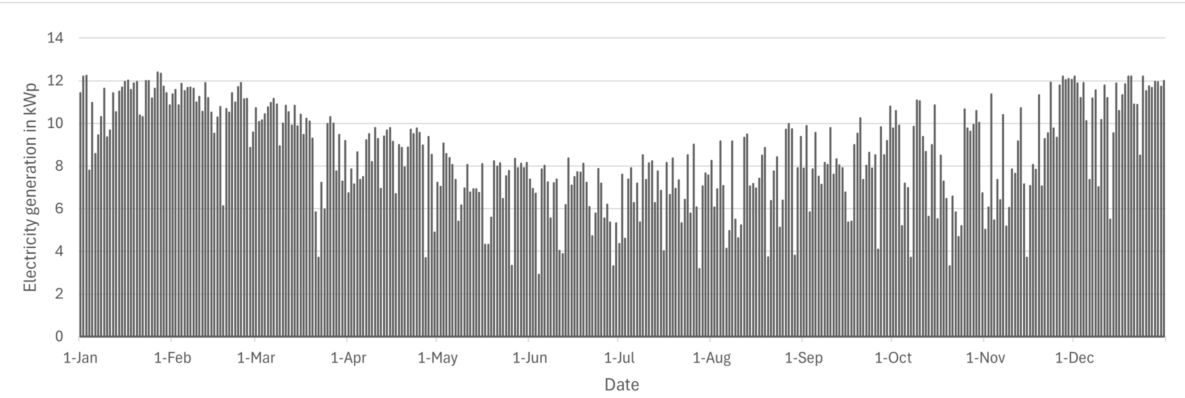


Figure 8.2: Generation profile of a 16 kWp micro-grid

Figure 8.2 illustrates the solar generation profile from a 16 kWp micro-grid in Sierra Leone. The data shows periods of lower and higher electricity generation, which feature two main seasons: the dry season (November-April) and the rainy season (May-October). During the dry season, increased sunlight, minimal rainfall, and extreme heat conditions lead to higher solar electricity output. Conversely, the rainy season is marked by reduced solar radiation due to frequent cloud cover, heavy rainfall, and severe weather conditions, resulting in lower solar generation. These seasonal differences in solar output emphasize the need to model each season separately to accurately assess the generation potential.

8.3.3. Electricity demand

Since the demand and supply must be balanced at each time step, electricity demand data is required as input for the model. Also, the electricity is provided as a fixed amount for each time step in the simulation. The demand profile is obtained from a grid operator in Sierra Leone. This data is provided as the total demand per minute for one day across the entire grid (160 kWp). Due to this one day data provision, it is assumed that the daily electricity demand for a day remains constant throughout the year.

The data is normalized and aggregated to hourly intervals. The data shows an outlier for the time period from 07:00 to 09:00. It is likely that these values remain constant or change very little during these periods, yet the data shows a 95% drop, as seen in Appendix C, section D.3. These anomalous values were replaced using forward filling, where the last known value is used to fill in the missing or incorrect values. Subsequently, the demand profile is scaled down to represent a 16 kWp micro-grid. As a results, the total average electricity load profile for the whole community, including businesses, households and a CHC is shown in Figure 8.3.

Figure 8.3 plots the total average electricity demand per hour. The load profile shows an evening peak, occurring from approximately 19:00 to 00:00, which can be explained by the absence of natural light during these hours and the fact that people are at home. The electricity demand at night can be explained by the use of electricity by CHC and businesses, the need for lighting and freezers for cooling products or vaccinations. The use of phone chargers and security lighting also contributes to the load at night [81].

The accuracy of the provided data is verified using the research of Mandelli et al. which gives the behavior of load profiles for off-grid rural areas. The research states that the electricity load for households in rural areas increases around 19:00, with a peak window of electricity consumption between 21:00 and 00:00 [81]. This is consistent with the data provided, where the load is higher from 19:00 to 00:00, with a peak at 21:00.

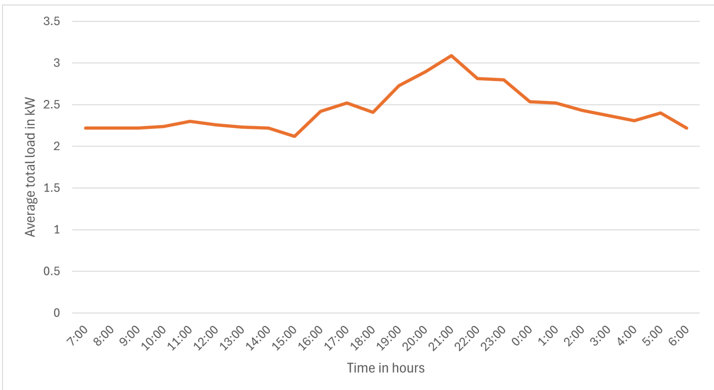


Figure 8.3: Total average load profile of a rural community used

The total load is divided over the total number of 58 connections. As a result, each connection follows the same load profile, regardless of whether it represents a household, business or a CHC. This is done based on the absence of specific household, business and CHC load profile data. In has no effect on the model results as these results are based on the total load of the system and not the load per connection. It only affects the power flow of the transmission lines, however this does not have a significant impact on the model results, see subsection 9.2.1.

8.4. Time

In this research, the operation of a micro-grid is assessed over a one-year period, divided into dry and rainy seasons to provide a clear understanding of the system's functioning in both conditions. Two representative months from each season are evaluated to reflect the entire year's performance. The dry season runs from November to April, with January and February used as input in the model. The rainy season lasts from May to October, with July and August selected for the model. The system's performance is analysed on an hourly basis.

8.5. Model output

As outlined in section 4.2, the primary KPI in this research is the average number of hours electricity is unavailable, measured as the Loss of Load Expectation (LOLE) hours. Additionally, the battery lifetime in cycles is also included as a KPI and indicates when replacement is needed. One cycle equals one day, so it is often expressed in days or years in this research.

Electricity can become unavailable due to frequency deviation, overload, loss of synchronisation, and voltage collapse [82]. In this model, unavailable electricity is considered when overload appears, meaning when demand exceeds the supply. Although this model may allow the analysis of factors, they are excluded from the analysis. This is because system overload is often the most common of system failure in rural developing areas, as identified and validated in chapter 5 and chapter 6.

8.6. Verification

This section focuses on the verification of the model. Verification ensures that the model functions correctly and produces the correct results, thereby guaranteeing the reliability and accuracy of the model's results. The model's behaviour is tested by checking whether its outcomes are logical and explainable, to check if the implemented code is correct. To achieve this, each run is conducted using the base model.

8.6.1. Behavior micro-grid PV production

Figure 8.4 illustrates the behaviour of the battery over an entire year. It is expected that the SoC of the battery will be higher during the dry season due to increased electricity production from stronger solar radiation compared to the rainy season. The figure shows that the SoC of the battery is divided into two groups, with one group having a higher average SoC than the other. This observed pattern is explainable and consistent with the expected behaviour of the battery.

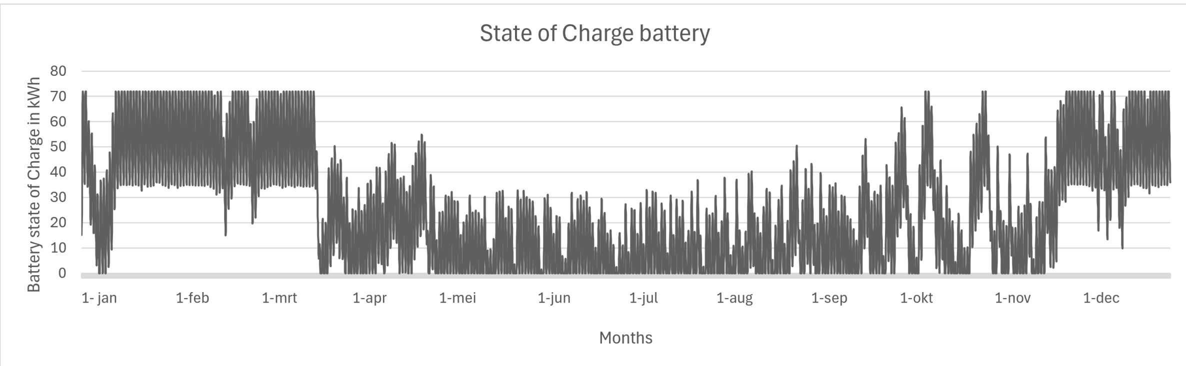


Figure 8.4: State of Charge of the micro-grid battery

8.6.2. Behavior micro-grid with and without battery

The expectation is that a micro-grid with a battery will have lower LOLE hours than a micro-grid without a battery. The battery provides electricity when the solar electricity generation is not enough, for exaple during dark hours. Figure 8.5 shows the number of days with LOLE hours during the rainy season (July and August) for a specific hour for a micro-grid with and without a battery.

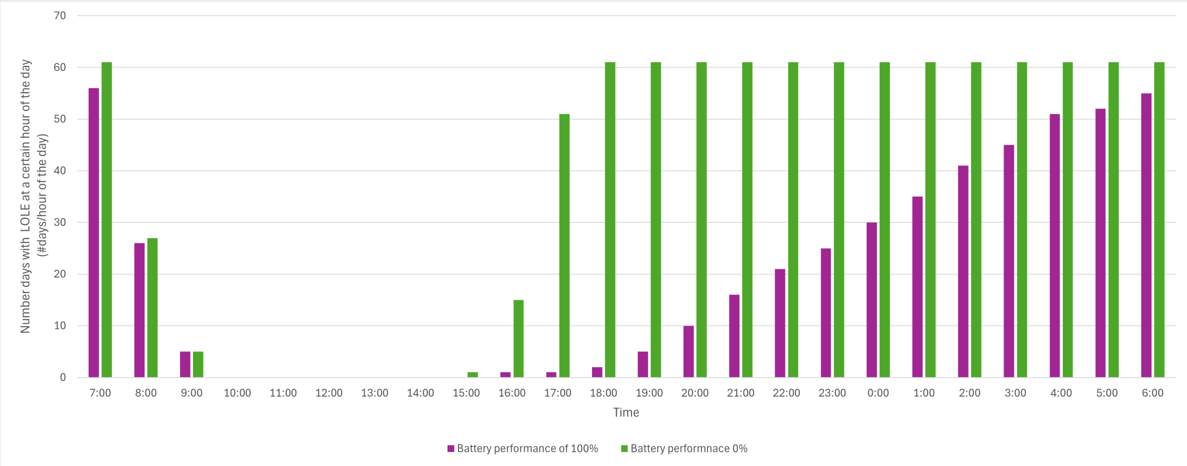


Figure 8.5: Number of days with LOLE per specific hour of the day in the rainy season

Figure 8.5 demonstrates that the micro-grid with a battery has fewer days with LOLE hours for a given time than a micro-grid without battery. At 22:00 a micro-grid with a battery has around 20 days in the months July and August with LOLE. While a micro-grid without a battery at 22:00 had around 61 days in the months July and August with LOLE. This indicates that the battery is providing power when there is no solar generation.

In conclusion, the model shows expected and explainable behaviour, confirming that it is sufficiently verified and thus well-implemented, and compliant with the model requirements.

8.7. Mitigation strategies in the model

This chapter outlines the experimental approach, including various runs with different inputs, to provide a comprehensive answer on which mitigation strategy is recommended. The first strategy focuses on demand control (DC), the second on cooling the batteries with air conditioning, and the third one on adding battery capacity. These three strategies are examined under varying levels of battery performance over a total of 36 experiments.

8.7.1. Demand Control

The mitigation strategy of demand control is implemented in the model. The DC strategy adopted is the DC before evening peak load. This allows the battery to recharge in preparation for the evening peak. This strategy ensures that the micro-grid is scheduled to be turned off from 16:00 to 19:00. An example period of three hours of micro-grid shutdown is set for this experiment, future studies could explore alternative time frames to evaluate the broader impact of varying shutdown periods. In this experiment, electricity is switched off for all businesses and households, while the model ensures that the electricity supply to CHCs is not switched off during these hours.

8.7.2. Air conditioning

In this strategy, the air conditioning is set at 25 degrees, which is a normal temperature for a battery to operate at [83]. Using air conditioning increases the electricity consumption. The room where the batteries are placed has no windows and is no larger than 20 m^2, therefor the cooling capacity between 1 - 3 kWh is required [84], [85]. Smaller air conditioners sufficient for the room typically consume between 2-5 kW per hour; once the room is cooled, the average consumption drops to around 0.75 kW per hour [86]. In this experiment, the load profile is increased by 0.75 kW per operating hour. The operating hours of the air conditioner are determined by the ambient temperature in Sierra Leone [69]. To maintain a constant 25 degrees, the air conditioner operates between 07:00 and 22:00, a total of 15 hours per day. Subsequently, the battery's lifetime is calculated using the 25-degree fade curve instead of the 45-degree fade curve.

8.7.3. Battery capacity increase

In this strategy, the effect of battery capacity increase on the Loss of Load Expectation (LOLE) hours is analysed, which can create a larger buffer to balance supply and demand and increase the electricity availability in the evening. The effect of the State of Charge (SoC) on the ageing rate has not been included due to limitations in the developed model. As the SoC level will decrease due to battery capacity increase, it remains a relevant factor to keep in mind. The battery capacity is increased by 10% under all the battery performance percentages to assess its impact on micro-grid electricity availability. This is an increase of 7.2 kWh. However, implementing this is costly, as the increase in battery capacity in this study is the most expensive option compared to the other strategies. An example of a storage increase of 10% is set for this experiment, to gain a broader understanding of the effects, future studies could assess the impact of storage increase.

9

Results

This chapter presents the findings of the model. The mitigation strategies and their corresponding results are examined in detail. Subsequently, a validation is conducted. Thereafter the results are discussed and compared with each other. Lastly, a sensitivity analysis is performed.

9.1. Base case: No action

9.1.1. Frequency of unavailable electricity hours

First, the results of the base case are generated to assess what the current state of the micro-grid is under normal conditions. This helps determine whether the micro-grid is sufficiently configured to meet demand and to identify potential weaknesses within the system.

In dry season

The number of days with LOLE hours within the two-month dry season (January and February) are shown in Figure 9.1. This means the number of days when electricity is unavailable at specific hours of the day within these two months.

The figure illustrates that around 7:00 there are more than 55 days with LOLE in dry season, for a battery performance of 40% and lower. With a battery performance of 100%, the grid will experience minimal issues. However, starting at a battery performance of 20%, there are almost 10 days with LOLE in the two months of the dry season where there is no electricity at 20:00. The figure shows that the number of days with LOLE hours increases both hourly as the day progresses and as the battery performance decreases.

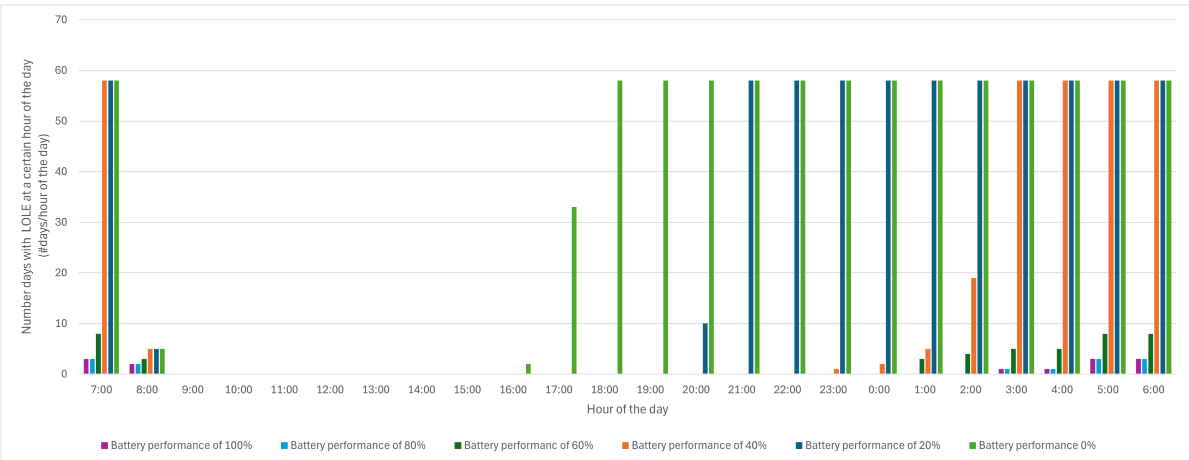


Figure 9.1: Number of days with LOLE per specific hour of the day in dry season (January and February)

In rainy season

Figure 9.2 shows the number of days with LOLE hours within the two-month in the rainy season (July and August). In the rainy season, the average number of days with LOLE hours is higher than in the dry season.

The figure illustrates that for all battery performance levels, the days with LOLE hours is 10 or more from 20:00 for every battery performance level. At 23:00 the number of days with LOLE is 35 or more, which means that about 50 % of the time there is no electricity at 23:00 in the months of July and August. For battery performance between 100% and 60%, the number of days with LOLE are almost the same for each hour. This can be explained by the fact that within this performance range, battery performance does not affect the number of days with LOLE for a certain hour.

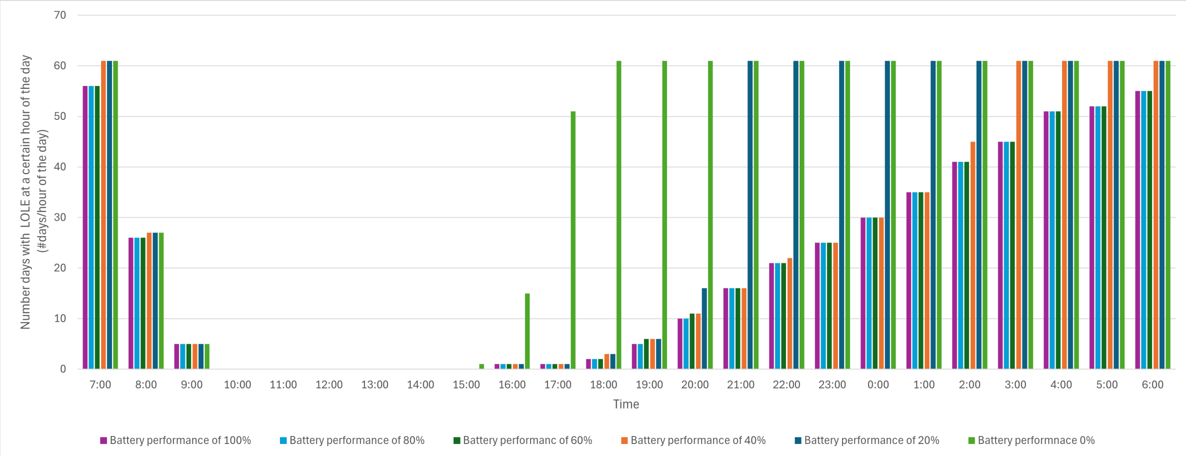


Figure 9.2: Number of days with LOLE per specific hour of the day in rainy season (July and August

9.1.2. State of Charge

In dry season

The difference in micro-grid performance is due to the variation in solar radiation between the dry and rainy seasons. This can be explained by the State of Charge (SoC) of the battery. During the dry season, a high SoC rate is detected,Figure 9.3, the battery mainly operates between a SoC of 72 and 35 kWh. From the SoC, it can be concluded that the battery frequently reaches its limit, indicating that storage capacity is a constraint.

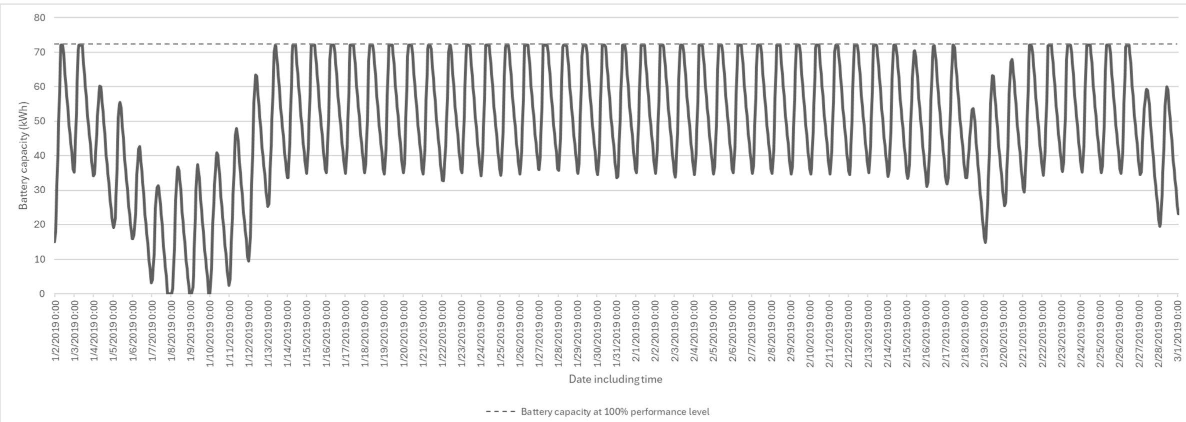


Figure 9.3: State of Charge battery in dry season for January and February

In rainy season

During the rainy season, however, the SoC is much lower. Battery capacity is no longer the primary issue. Rather, the problem is one of insufficient generation or excessive demand. Reasoning suggests that this is primarily due to reduced power generation during the rainy season, as the load remains constant during both seasons.

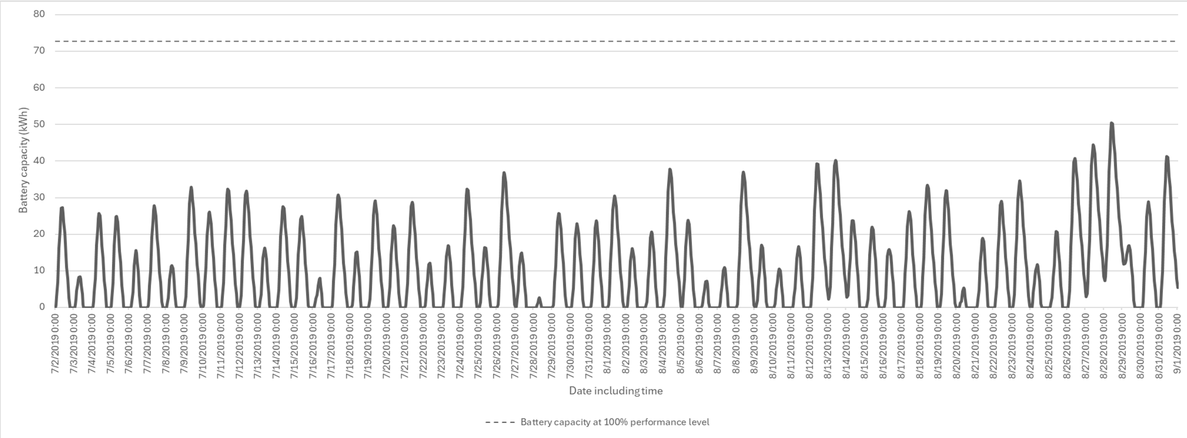


Figure 9.4: State of Charge battery in rainy season for July and August

9.1.3. Battery performance

Day requirement

For the micro-grid performance system requirements are identified, see section 4.2. During the day, micro-grids are permitted to have a maximum of 8 LOLE hours per day. Based on this requirement the limit is set, Figure 9.5 shows the maximum allowable LOLE hours per day, which is set at 8 hours.

Figure 9.5 shows again that the rainy season has a lower performance compared to the dry season and struggles to meet the system requirement.

In both seasons, battery performance up to 65% does not affect the LOLE hours. However, beyond a battery performance of 65%, the LOLE hours start increasing. In the dry season, the limit is reached when the battery performance drops to around 33%. In the rainy season, this occurs at 55%, indicating the need for mitigation strategies. This results in a 27% difference in battery performance between the rainy and dry seasons.

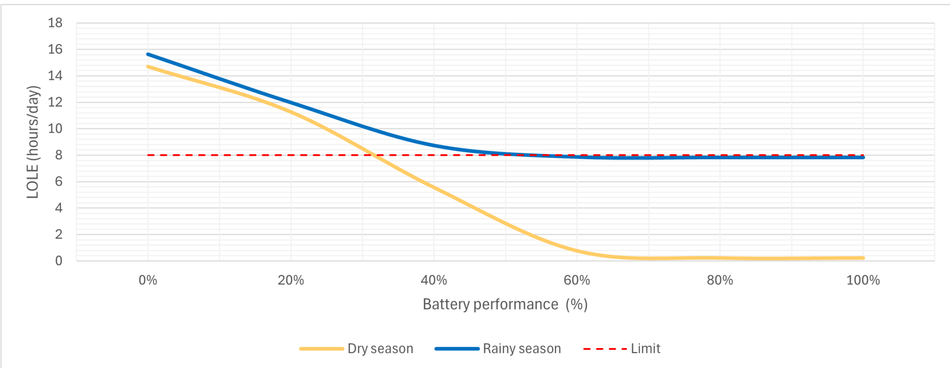


Figure 9.5: Loss of Load Expectation hours with battery performance during a day

Night requirement

The system night requirement is that micro-grids are permitted to have a maximum of 8 LOLE hours per night. The evening hours are defined as the period without sunlight, from 19:00 up to 07:00. Figure 9.6 shows the LOLE hours during the evening and provides a more detailed view of how long the battery supplies electricity. The difference between the LOLE hours in Figure 9.5 and Figure 9.6, represents the number of LOLE hours occurring during the day due to electricity shortages.

The night requirement is met during the rainy season, which seemed to be the case in Figure 9.5. The difference between the night requirement and the LOLE hours at night is larger than the daily overview reveals. In the rainy season, the system night requirement is reached at 34% battery performance, compared to 28% in the dry season. The rainy season is therefore the limiting factor in terms of electricity availability, requiring strategies to improve the micro-grid performance beyond these points.

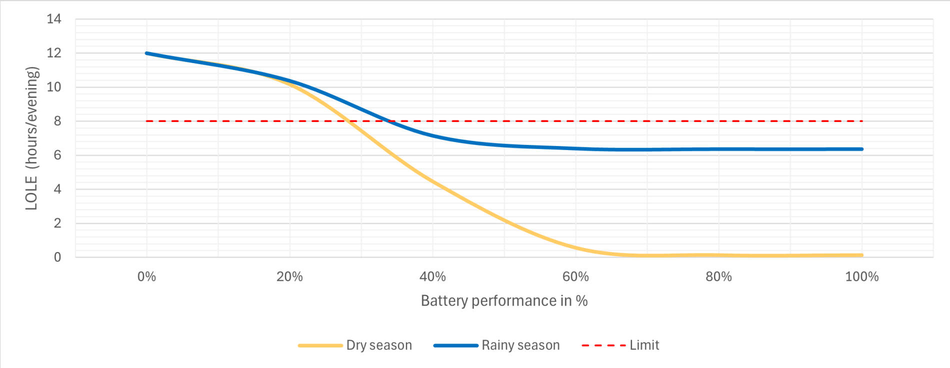


Figure 9.6: Loss of Load Expectation hours with battery performance during the night

9.1.4. Battery lifetime

The battery's lifetime indicates how many days the battery will operate, assuming one cycle per day. When the system requirement is reached, the battery must be replaced to continue the micro-grid performance between the system requirements. Figure 9.7 shows that in the rainy season after around two years, the battery will not work sufficiently. The system requirement is reached after 750 days in the rainy season when performance falls below the required standard. In the dry season issues arise around 1000 days. This graph, Figure 9.7 confirms that the rainy season is the limiting factor, with a difference of 250 days. To meet system requirements throughout the year, the battery will need to be replaced after 750 days. The battery has a performance level of 0% after 2125 days, the battery is no longer operational.

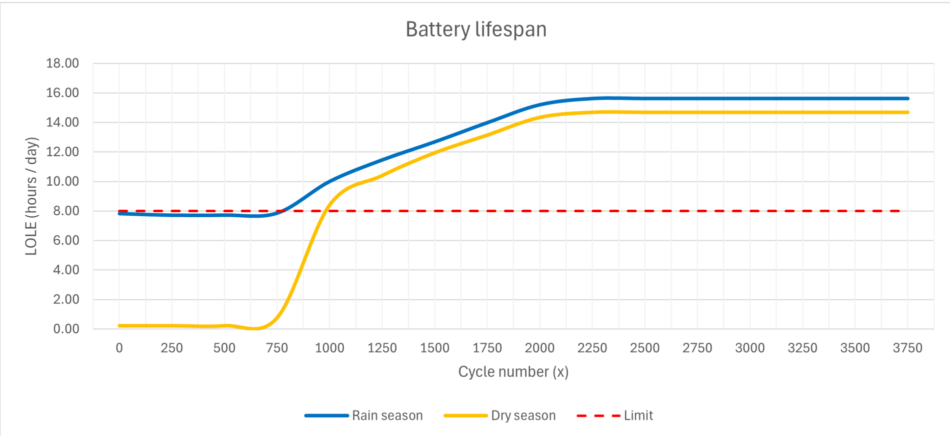


Figure 9.7: Battery lifetime

9.2. Model Validation

Validation is a method used to assess whether the model aligns sufficiently with empirical observations, in other words, with reality. If the model lacks validity, it does not tell enough about the real system and the results are not valid. Various approaches can check whether the model is sufficiently valid.

One approach is to compare existing data and model results. The model behaviour of the SoC of the battery is compared with available data from a specific micro-grid in Sierra Leone. This data includes the SoC percentages of the battery per minute for a day during the rainy season. Analysis of the battery behaviour from the data provided shows that the battery in the model has similar behaviour for a day during the rainy season, see Figure 9.8. This confirms that the model is valid. However, the SoC values do not match exactly. This difference could be due to a number of factors, with differences in solar generation being the most likely explanation.

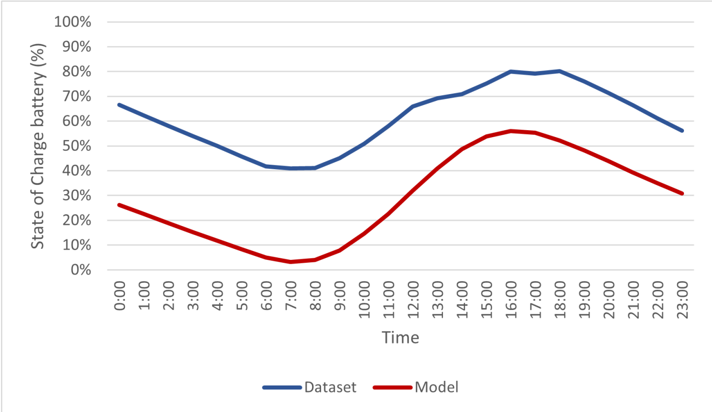


Figure 9.8: Validation of the State of Charge

In addition, the lifetime of the battery can also be validated. The approach used to verify the validity of this KPI is through expert interviews. An expert interview confirms that batteries in Sierra Leone operate for half of their estimated lifetime. This is because local conditions accelerate the degradation process of lead-carbon batteries under normal conditions. The average lifetime of batteries in Sierra Leone is approximately 5 years [38] The estimated fade curve, Figure D.5, indicates a battery lifetime of 2,125 days, 5.8 years, which is consistent with the results of the expert interviews. Under normal conditions, lead-carbon batteries have an expected life of around 10 years or 3,500 cycles [87]. The estimated fade curve at 25 degrees in Figure D.5, shows a lifetime of 3,600 days which is in line with the expert statement. It can be concluded that the KPI lifetime is valid and is sufficiently consistent with reality.

9.2.1. Sensitivity analyses

As part of the validation process, a sensitivity analysis is conducted to assess the influence of input parameters on the KPIs. This analysis is crucial, given that many input parameters in this model are estimated or assumed.

The primary input parameters considered in this model include the topology, solar system and storage characteristics, and load and generation profiles. A detailed overview of these input parameters can be found in subsection D.2.3. For the sensitivity analysis, parameters with uncertainty in the model were selected: the load profiles, storage efficiency, transmission line length and transmission line type. Solar and storage capacity, as well as the generation profile, are excluded from the first sensitivity analysis because it is clear that changes in these parameters would affect the KPIs. Although this also applies to the load profiles, they are included in the analysis due to the high level of uncertainty associated with user behaviour. The extended fade curve can also affect the KPIs. However, the fade curve influences only the lifetime of the battery and not the LOLE, as it is applied only when calculating the lifetime. In addition, since the same curve is used for each experiment, except the air conditioning experiment, it only affects specific values rather than comparisons between scenarios.

The sensitivity analysis starts with a base case run to establish baseline values for the KPIs: electricity unavailability and battery lifetime. This is to determine which of the selected parameters have a notable impact. Based on these results, the sensitivity analysis is carried out for the different experiments. This approach is chosen because of time constraints. The specific input parameters are adjusted one at a time; the load, storage efficiency and length of transmission lines is decreased by 20% and a different type of transmission line is selected, while the other parameters remain constant. This approach allows for assessing the impact of each parameter on the KPIs relative to the baseline scenario. Figure 9.9 shows the sensitivity analysis.

	Base case		Load - 20%		Battery efficiency - 20%		Line length - 20%		Line type change	
	LOLE day	LOLE evening	LOLE day	LOLE evening	LOLE day	LOLE evening	LOLE day	LOLE evening		LOLE evening
Battery performance of 0%	**15.62**	**12.00**	-4.72%	0.00%	0.00%	0.00%	0%	0%	0%	0%
Battery performance of 20%	**11.97**	**10.38**	-13.42%	-13.11%	6.03%	6.16%	0%	0%	0%	0%
Battery performance of 40%	**8.72**	**7.15**	-38.16%	-43.12%	26.32%	30.73%	0%	0%	0%	0%
Battery performance of 60%	**7.85**	**6.39**	-58.87%	-59.74%	39.25%	44.87%	0%	0%	0%	0%
Battery performance of 80%	**7.82**	**6.36**	-62.68%	-63.66%	39.83%	45.62%	0%	0%	0%	0%
Battery performance of 100%	**7.82**	**6.36**	-62.68%	-63.66%	39.83%	45.62%	0%	0%	0%	0%

Figure 9.9: Results of the sensitivity analysis

The sensitivity analysis confirms that the relationships between the parameters and the KPIs align with the expectations. The expectations of the sensitivity analyses are explained in Appendix C. The model is not sensitive to changes in transmission line length or changes in the transmission type. This does not affect LOLE hours, as the reduction in transmission losses is minimal. Although outcomes show that both do impacts the SoC, see Appendix D, section D.5, however the effect is too small to influence LOLE hours, as shown in Figure 9.9.

The sensitivity analysis shows that the model is particularly sensitive to parameters associated with load and battery efficiency changes, as these directly impact the available electricity, see Figure 9.9. In the sensitivity analysis with reduced load, there is a more notable reduction in LOLE hours when the battery is at 100% performance compared to 20%. This is because a battery at 100% can operate at full capacity. At 20% performance, the battery already struggles to meet demand, making load reductions less effective, as LOLE hours are already frequent. In contrast, at 100% performance, the battery has sufficient capacity to prevent LOLE hours, and reduced load further decreases the LOLE hours. The same principle applies to battery efficiency. In section 9.7, this sensitivity is further examined to determine whether it affects the final mitigation strategy. If the final results remain unchanged, it can be concluded that the model is not sensitive.

9.3. Demand Control regulations

9.3.1. Battery performance

Day requirement

In dry season Figure 9.10 shows results in an increase in LOLE hours during the day for all battery performance levels. This is because demand control (DC) involves a standard electricity cutoff between 16:00 and 19:00. The day requirement of a maximum of 8 LOLE hours per day, is now achieved at an earlier performance percentage. The additional 3-hour electricity cutoff is not fully compensated by the system at other times of the day, resulting in a higher overall LOLE hours.

In the rainy season, the difference in LOLE hours between no action and DC is smaller compared to the dry season. This indicates that, despite the additional 3 hours of no electricity, the increase in LOLE hours is limited. At a battery performance of 60%, the number of LOLE hours per day is similar between no action and DC. Therefore, the additional 3 hours of no electricity are compensated by a LOLE reduction elsewhere. The turning point is observed at 65% battery performance. Up to this level, DC has added value. Beyond this point, a trade-off must be made between the number of LOLE hours during the day and LOLE hours in the evening.

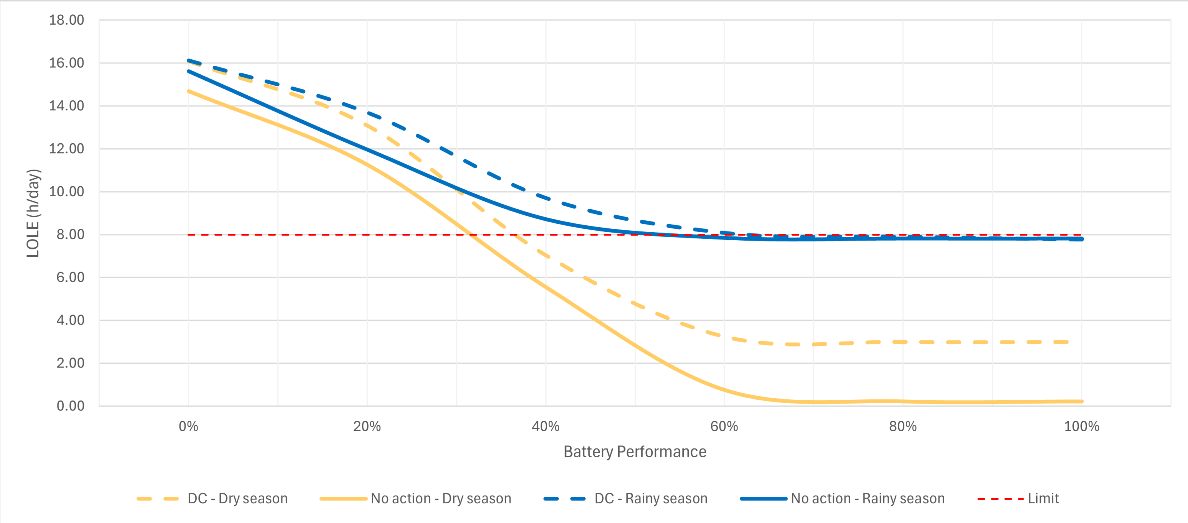


Figure 9.10: Loss of Load Expectation during a day

Night requirement

DC increases the total number of LOLE hours throughout the day, as shown in Figure 9.10. However, DC reduces the number of LOLE hours specifically during the evening, as demonstrated in Figure 9.11. In the dry season, a closer examination of the evening hours reveals that the additional electricity provided in the evening does not apply uniformly across all battery performance levels. Specifically, DC has no effect in the dry season when battery performance ranges between 100% and 60%. A notable difference emerges in the number of LOLE hours during the evening when battery performance is between 60% and 20%, where DC shows a noticeable impact.

DC has a higher effect in the rainy season than in the dry season. The number of LOLE hours is extended by more than two hours for battery performance levels up to 50%. Beyond 50%, the additional hours gained in the evening due to three hours of DC start to decrease. However, DC still maintains a consistently higher impact in the rainy season compared to the dry season, regardless of battery performance. In the rainy season, the night requirement is reached at a battery performance of 24%, resulting in no electricity availability at 23:00. Without DC, this requirement is reached at a battery performance of 34%. Since evening electricity is a critical requirement for the system's users, DC can decrease the LOLE hours in the evening during the rainy season.

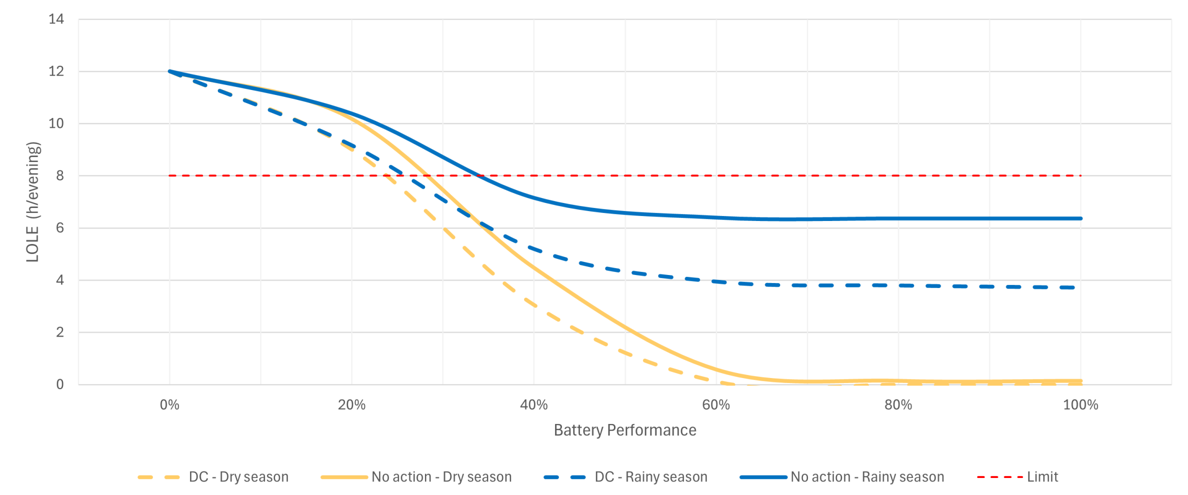


Figure 9.11: Loss of Load Expectation during a night

9.3.2. Lifetime

Figure 9.12 shows the lifetime of the battery. The system requirement of maximal 8 LOLE hours per day with DC in the dry season is reached after approximately 900 cycles. Without DC, it is reached after about 1000 cycles. The figure illustrates the battery's lifetime, which is approximately 2125 days in total at a 0% performance level. This is regardless of the strategy used, as it is the same as in the base case. The lifetime in the rainy season shows that the system requirement is reached in an early state with or without DC around 750 cycles. This indicates a battery replacement after 2 years.

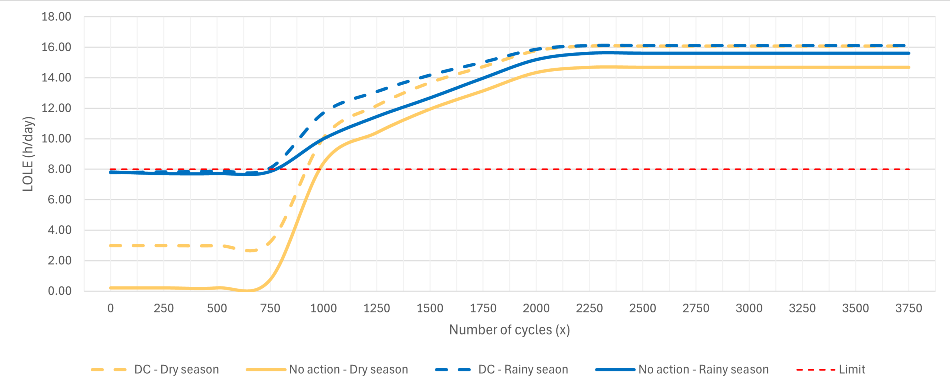


Figure 9.12: Lifetime of battery with and without DC

9.4. Implementation of air conditioning

9.4.1. Battery performance

Day requirement

The LOLE hours increases with the use of air conditioning. The increase in LOLE hours is notably higher in the rainy season than in the dry season. This is due to the existing electricity shortages during the rainy season, see Figure 9.4. The use of air conditioning increases the electricity demand, which increases the LOLE hours, shown in Figure 9.13.

In the dry season for a battery performance of 38%, the system requirement is reached with air conditioning, whereas, without air conditioning, the requirement is reached at a performance of 28%. Air conditioning is inefficient for meeting the system day requirement.

The same applies to the rainy season, but the effects are even more pronounced. Using air conditioning during the rainy season results in the LOLE hours exceeding the requirement at a 100% battery performance.

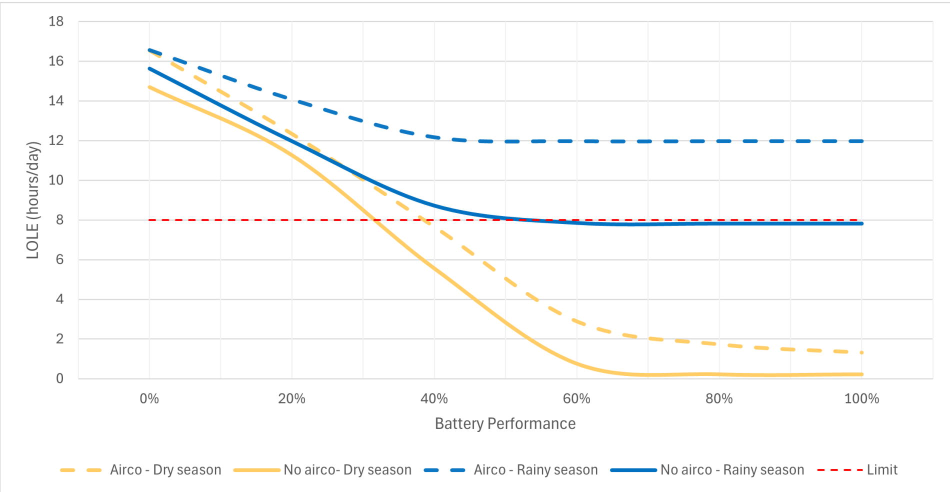


Figure 9.13: Loss of Load Expectation for a day in dry and rainy season

Night requirement

To meet the system night requirement, the air conditioning has no positive impact. In the dry season, air conditioning has less impact on the LOLE hours compared to the rainy season. In the dry season, the night requirement is reached with air conditioning at 35% battery performance. Without air conditioning, it is reached at 28%, showing a negative battery performance level increase of 7%, see Figure 9.14.

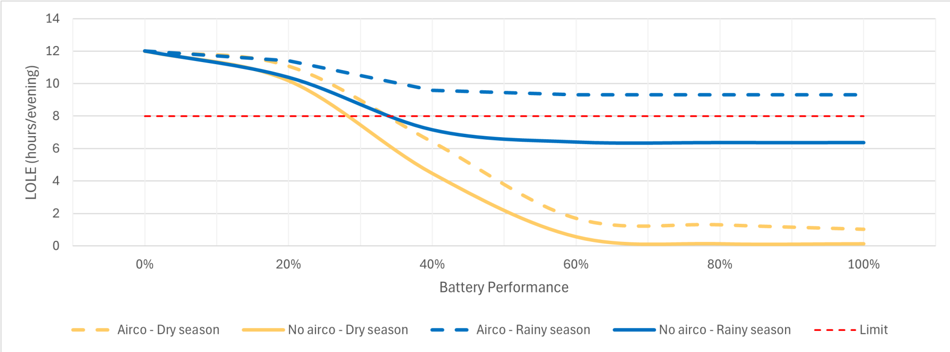


Figure 9.14: Loss of Load Expectation for a night in rainy and dry season

9.4.2. Life cycle

Looking at the total battery lifetime, with air conditioning the lifetime of the battery is 3,750 days, compared to 2,125 days. This leads to an extension of 4.8 years, but the battery will be operating below system requirements for some time.

During the dry season, the use of air conditioning extends the battery's lifetime. Taking into account the daily requirement of 8 LOLE hours per day, the use of air conditioning extends the life by 250 days. Using air conditioning, the battery needs to be replaced after 3.4 years. This accounts for the dry season, but since the rainy season determines the battery replacement lifetime, this will have no effect. Air conditioning has no positive impact during the rainy season. It has a negative effect because the system already exceeds system requirements from the beginning of the number of life cycles, see Figure 9.15.

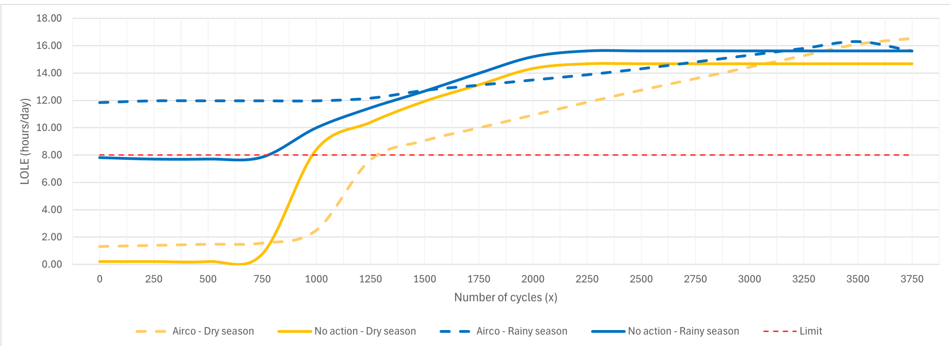


Figure 9.15: Lifetime battery with and without air conditioning

9.5. Battery capacity increase

9.5.1. Battery performance

Day requirement

Considering the evening requirement, battery capacity has a more positive impact on the LOLE hours in the dry season than in the rainy season. This is because, during the dry season, the State of Charge (SoC) frequently operates near its maximum charge level, see Figure 9.3, allowing additional battery capacity to have an impact.

For the dry season, adding additional battery capacity results in a decrease of LOLE hours and allows for lower battery performance, see Figure 9.16. The system requirement is reached at 20% with extra battery capacity. Without additional battery capacity, it is reached at a performance of 32%. Adding 10% extra battery capacity allows for a 12% higher minimal battery performance percentage.

In the rainy season, adding battery capacity does not negatively affect the LOLE. At a battery performance level of 50%, the LOLE hours exceeds the system requirement, similar to when no action is taken. However, this measure helps to maintain the LOLE hours at a lower level. Increasing the battery capacity by 10% does not notably reduce the LOLE throughout the day.

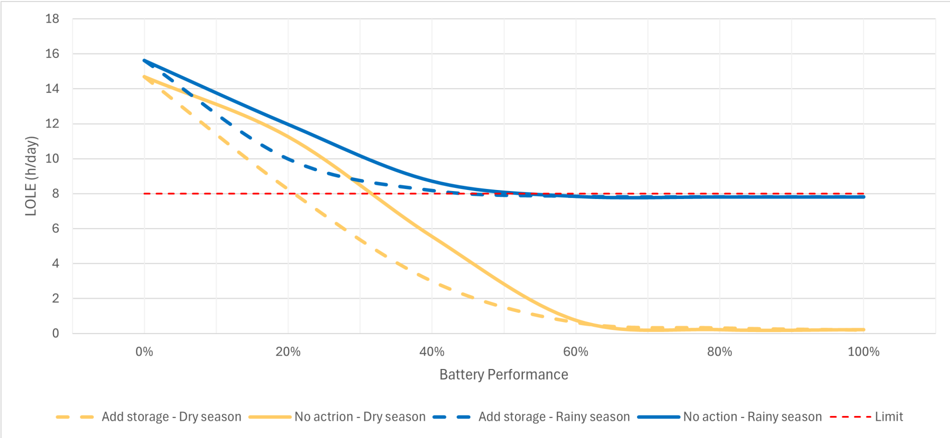


Figure 9.16: Loss of Load Expectation additional battery capacity for a day

Evening requirement

The same applies more precisely for the evening, see Figure 9.17. In dry season the impact is higher. An additional 10% in battery capacity results in an increase in the battery performance level. With additional battery capacity, the battery performance level is set of 26%. However, a closer examination reveals that the increase in battery capacity also leads to a 10% extension in battery performance level during the rainy season. In the 'no action' experiment, the system requirement is reached at a battery performance of 35%. With additional battery capacity, it is reached at a performance of 25%.

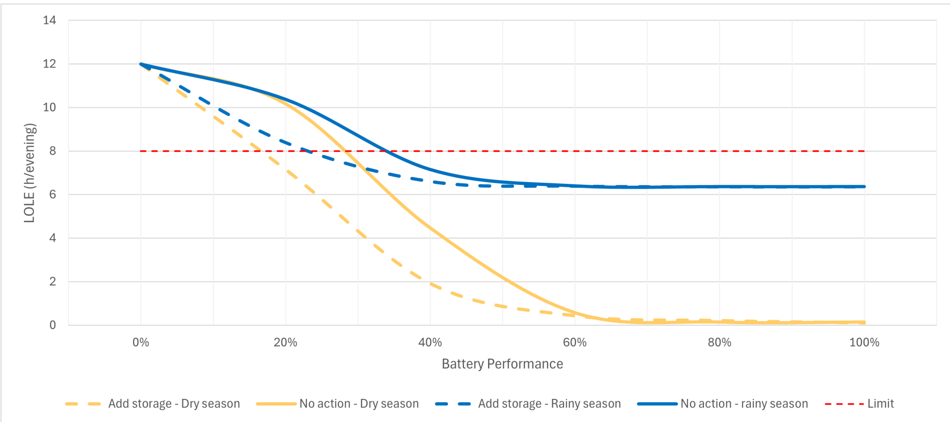


Figure 9.17: Loss of Load Expectation additional battery capacity for a night

9.5.2. Life cycle

In both cases, adding battery capacity extends the battery's lifetime without increasing the number of LOLE hours, in contrast to the air conditioning experiment. In the rainy season, the extension is 250 days until the requirement is reached, as shown in Figure 9.18.

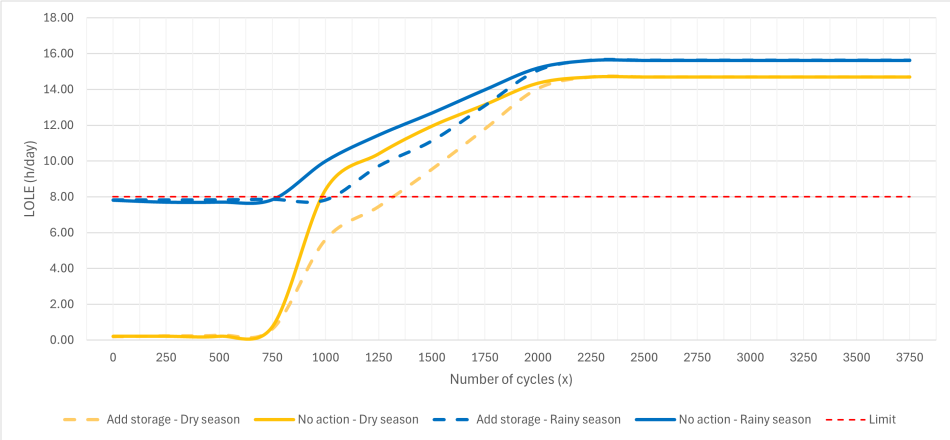


Figure 9.18: Lifetime battery with and without additional battery capacity in both seasons

9.6. Result discussion

9.6.1. A comparative analysis of the experimental results

This section compares and discusses the impact of the three mitigation strategies to in the end give advice on possible mitigation strategies. The impact of the mitigation strategies is analyzed separately for the rainy and dry seasons, as the SoC and LOLE hours differ between these seasons, which may indicate that different strategies are suitable for each season.

9.6.2. Battery performance in rainy season

Day requirement

An analysis of all the strategies in Figure 9.19 shows that no notable LOLE hours reduction is achieved for all mitigation strategies. However, the addition of battery capacity does allow a lower minimal level of battery performance from 55% to 45%. It can be concluded that the addition of battery capacity in the rainy season results in a lower battery performance level. The requirement of a maximum of 8 LOLE hours per day is now reached at a lower battery performance level. But this does not lead to a reduction in the overall LOLE hours during the day. The other strategies similarly do not demonstrate a decrease in LOLE hours or lower battery performance level throughout the day.

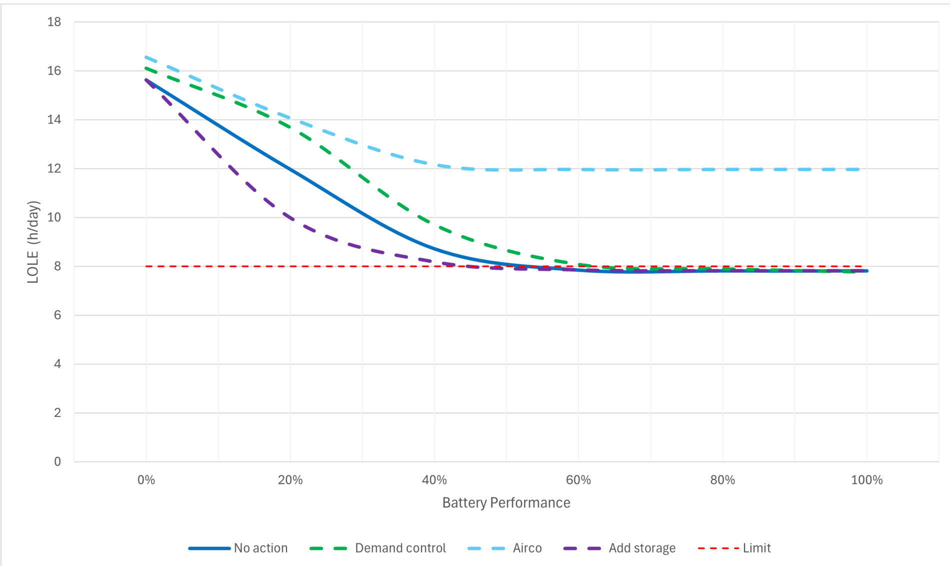


Figure 9.19: LOLE of the mitigation strategies in rainy season during the day

Night requirement

A closer examination of the evening hours reveals that the strategies do have an impact on the night requirement, as shown in Figure 9.20. DC has the most notable effect on reducing the LOLE hours, while the other solutions do not achieve this. DC shifts no electricity hours to the afternoon, extending electricity availability in the evening. However, this does not result in a decrease in the total number of LOLE hours throughout the day, as seen in Figure 9.19. At 100% battery performance, the number of LOLE hours decreases by more than 2 hours, although this reduction decreases as battery performance is lower.

A lower battery performance level is achieved with DC because the reduction in LOLE hours delays the time before the threshold is reached. Increasing the battery's performance level from approximately 34% to 26%. This is also observed with the addition of extra battery capacity. While the battery capacity has a minimal impact on reducing LOLE hours, it achieves the lowest possible battery performance level, lower that achieved with DC. Among the three strategies, air conditioning has a negative effect on both LOLE hours and battery performance level.

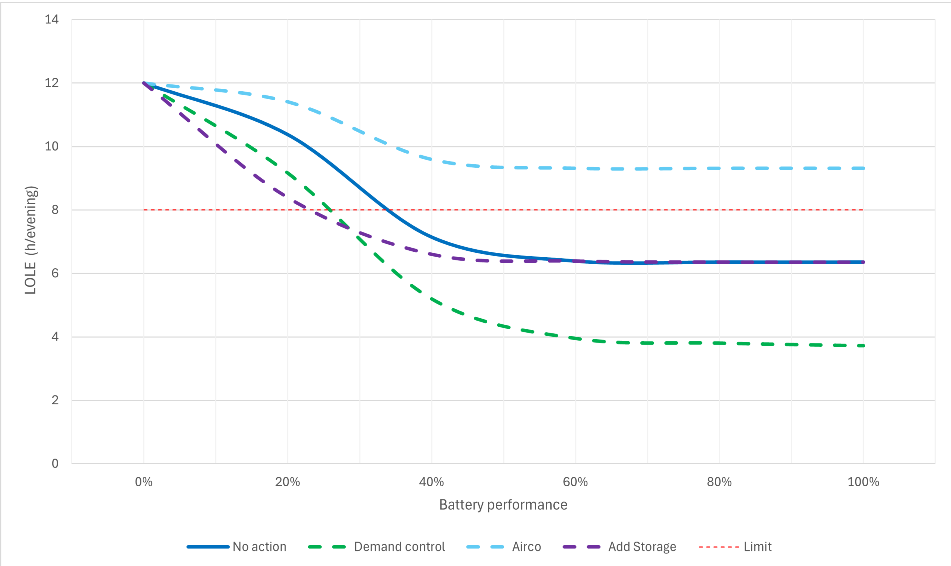


Figure 9.20: LOLE of the mitigation strategies in rainy season during the night

9.6.3. Battery's lifetime in rainy season

As shown in Figure 9.21, using air conditioning delays the battery's degradation process. However, the battery consumes too much electricity for this strategy to be feasible within the current micro-grid. Figure 9.19 demonstrates that both DC and the addition of battery capacity reduce the battery performance level, directly affecting its replacement lifetime. Both strategies extend the time to reach this threshold compared to taking no action, but they do not extend the total operating lifetime of the battery.

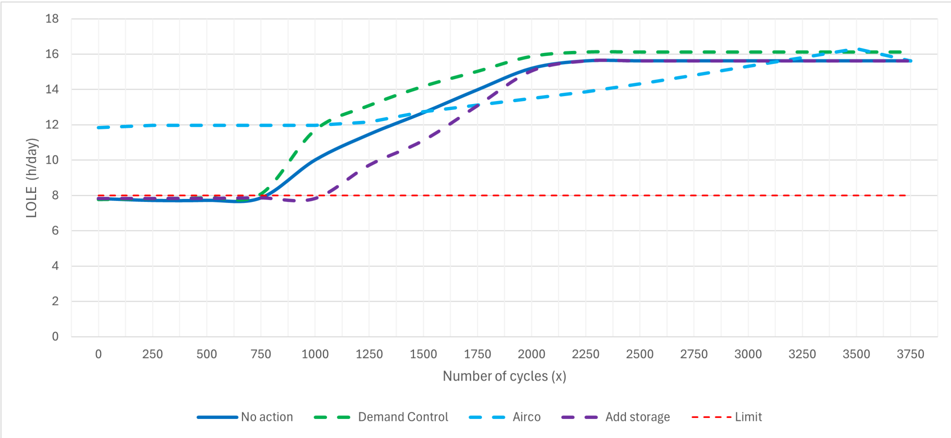


Figure 9.21: Overview of battery lifetime in the rainy season for the experiments

9.6.4. Battery performance in dry season

Day requirement

Over the entire day, adding battery capacity slows the increase in LOLE hours. As shown in Figure 9.22, the system requirement is reached at a lower battery performance level compared to no action, allowing for a lower minimum battery performance level. The requirement is reached at 20% battery performance with additional battery capacity. Without extra battery capacity, it occurs at a 32% performance level. The addition of 10% extra battery capacity permits a 12% lower battery performance level. This is not the case for either DC or air conditioning. These strategies, when evaluated over the entire day, do not have a positive impact on the LOLE or the battery performance level.

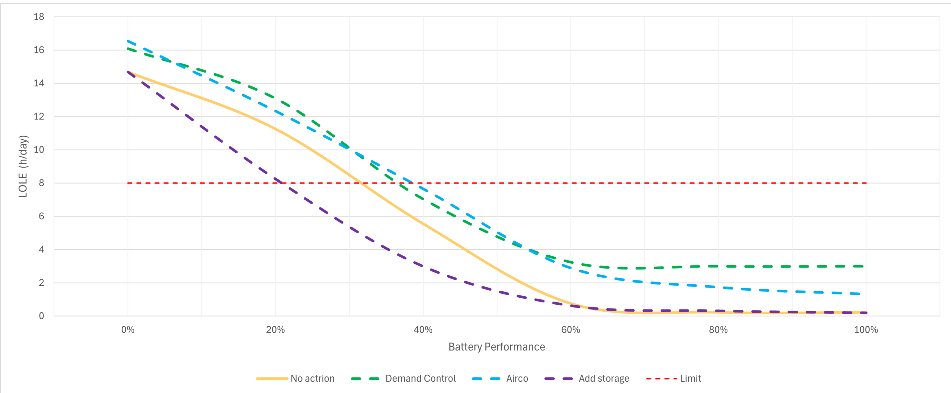


Figure 9.22: LOLE of the experiments in dry season during the day

Night requirement

In the evening hours, a similar trend is observed in Figure 9.23. The battery performance level decreases with the addition of extra battery capacity. In addition, DC also has a notable effect on reducing LOLE hours and minimum battery level, although the effect is more limited than adding additional battery capacity. Air conditioning, however, has a negative effect on both the LOLE hours and battery performance tolerance.

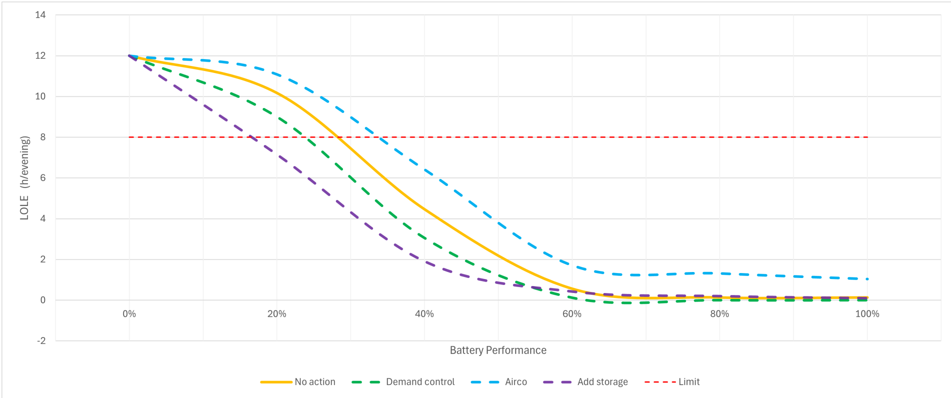


Figure 9.23: LOLE of the experiments in dry season during the night

9.6.5. Battery's lifetime in dry season

Both air conditioning and additional battery capacity extend the battery's lifetime by approximately 250 days, as shown in Figure 9.24. Results show that air conditioning does not fit within system requirements, so adding battery capacity will be more favourable. In contrast, DC does not extend the battery's lifetime. It increases the LOLE throughout the day, leading to an earlier replacement and shorter battery lifetime.

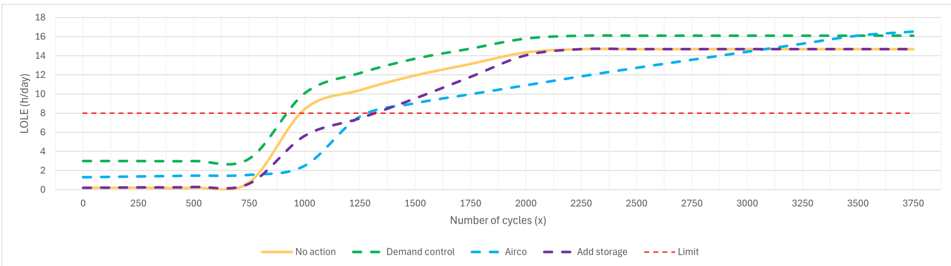


Figure 9.24: Overview of battery lifetime in the dry season for the experiments

9.6.6. Demand control versus battery capacity increase

Since DC and adding battery capacity compete with each other, a results discussion between these two strategies is included. Firstly, battery capacity increases battery lifetime, resulting in a longer period between replacements compared to DC. Figure 9.25 presents the battery performance percentages at which the requirement is met. The highest minimum battery performance level for each mitigation strategy ultimately determines at which battery performance level micro-network performance issues arise, highlighted in bold.

Considering both day and night requirements, adding battery capacity is the only solution. In the rainy season, micro-grid performance issues arise when battery performance falls below 45%, while performance issues occur in the evening at performance levels starting from 24%.

Focusing solely on the night requirement, identified as the most crucial requirement from site visits, performance issues with DC arise at a battery performance of 25%. This difference is negligible compared to the 24% when adding battery capacity. Furthermore, DC extends evening light availability. Adding battery capacity does not, as there is insufficient electricity to store in the rainy season and no performance issues in the dry season.

Day requirement

	Battery capacity increase			DC	
	New %	Old %		New %	Old %
Rain	45%	52%	Rain	63%	54%
Dry	21%	32%	Dry	35%	32%

Night requirement

	Battery capacity increase			DC	
	New %	Old %		New %	Old %
Rain	24%	35%	Rain	25%	36%
Dry	15%	28%	Dry	24%	28%

Figure 9.25: Minimal battery performance percentage to meet system requirements

9.7. Sensitivity analysis of results

A sensitivity analysis is performed on the different strategies to determine whether a change in sensitive parameters leads to different outcomes. The sensitivity analysis in subsection 9.2.1 demonstrates that changes in demand and battery capacity efficiency are sensitive. This sensitivity analysis examines whether this sensitivity also affects the conclusion regarding which mitigation strategy is recommended. The same approach as in the first part is used, however, the input parameter of the load is increased by 5%.

The sensitivity analysis confirms that the load is not sensitive, and the conclusion remains consistent with the outcomes of the experiments, see Figure 9.26 and Figure 9.27. DC remains the most effective strategy in the evening, followed by the addition of battery capacity, maintaining the overall result unchanged.

Only the load parameter is tested in this sensitivity analysis due to time constraints and the fact that this parameter is the most sensitive in subsection 9.2.1. The effect of an increase in battery efficiency can be reasoned. Higher battery efficiency increases available electricity. Additional battery capacity has a minimal impact during the rainy season due to the low generation, see Figure 9.4. Air conditioning only extends its lifetime but does consume extra electricity leading to higher LOLE, maintaining the overall results unchanged.

Figure 9.26: Sensitivity analyses strategies in day time in rainy season

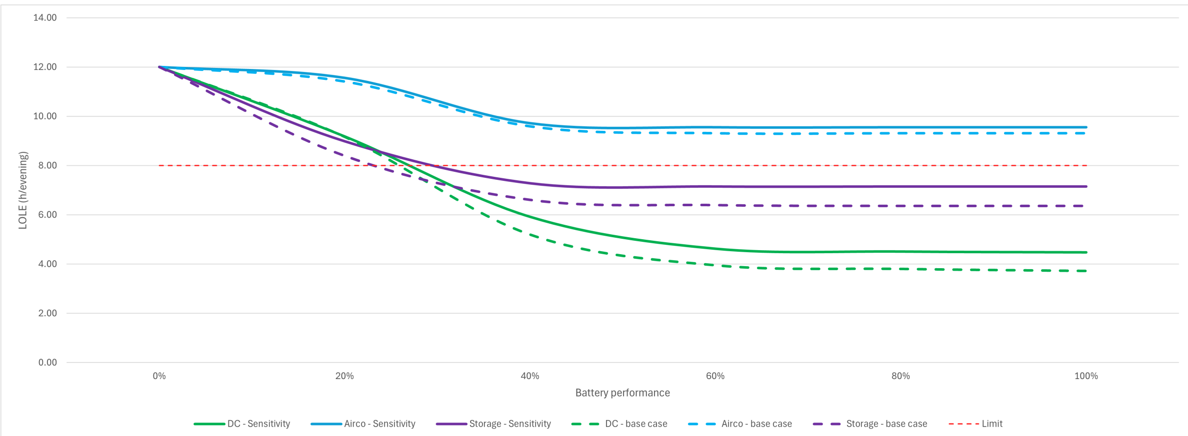


Figure 9.27: Sensitivity analyses strategies in evening in rainy season

10 Conclusion

Nowadays, rural developing areas still have little or no access to electricity. Solar micro-grids are presented as a solution to provide electricity to these areas. Although micro-grids have been installed in rural development areas, problems with access to electricity remain. The micro-grids face performance issues. Numerous factors which impact micro-grid performance have been identified in the literature. However, these factors vary between studies, and their impact on the performance of the micro-grid is often not thoroughly addressed. This research aims to identify and validate the factors that influence micro-grid performance in rural developing areas. It will then assess the impact of the most relevant factor and explore appropriate strategies to mitigate the impact on the performance. This is done through a case study, which serves as a general approach for micro-grids in rural developing areas. Six sub-questions are addressed to ultimately provide an answer to the main research question and in addition, make recommendations regarding these micro-grids

> ***SQ 1:*** *What is the current situation of solar micro-grids in rural developing areas?*

The current situation of micro-grids in rural developing areas indicates that their operation is under pressure. Micro-grids in rural developing areas struggle with performance issues. Performance issues are partly due to the regulatory, technical and economic environment in which micro-grids operate. An environment without favourable micro-grid regulations hinders the profitability of micro-grid operators. A lack of financial resources hinders system improvements and leads to performance degradation. Performance issues reduce user satisfaction and willingness to pay, further worsening the financial situation of the micro-grids. Grid-operators rely on funding and favourable government regulation to keep micro-grids operational. Grid operators need to find alternative strategies, to improve the micro-grid's performance and in the end the access to electricity.

> ***SQ 2:*** *What are the most relevant Key Performance Indicators and the system requirements for solar micro-grids in rural developing areas?*

To improve the system's performance, clear performance indicators and system requirements must be established. It is recommended to consult with system users to determine the specific performance indicators and requirements the micro-grid system must meet.

Users consider the availability of electricity as important. Electricity enhances living standards and supports economic development. Therefore, the performance indicator for micro-grids in rural areas is measured by the average number of hours electricity is unavailable. This is measured in the Loss of Load Expectation (LOLE) hours, a commonly used KPI in the literature.

Another KPI used in the research is the lifetime of the battery since the battery is identified as the most relevant factor. The battery lifetime is measured in the number of cycles. One cycle accounts for one day. The battery performance decreases over time. After several years, battery performance affects the electricity availability, causing the system to fail to meet its system requirements. If the system requirements are no longer met, battery replacement is recommended.

Micro-grids in rural developing areas with connected households, businesses, and CHCs are allowed to experience a maximum of 8 LOLE hours per day and a maximum of 8 LOLE hours in the evening after sunset, according to the multi-tier framework in terms of electricity availability. These are therefore the system requirements in which the micro-grid must operate. The evening requirement is considered the primary requirement because electricity during this time extends productivity hours.

SQ 3: *Which factors affect the performance of micro-grids in rural developing areas?*

Micro-grids are installed in an existing environment. This environment contains factors that influence the micro-grid performance. The factors commonly mentioned in the literature as influencing the performance of micro-grids are identified and classified into social and technical categories. Key technical factors include system design, local technicians, and exceptional events, while social factors encompass community behaviour, ownership model, and system security.

The identified factors are present in many micro-grid systems, however, some factors occur more frequently than others. Based on field research and semi-structured interviews with experts, the occurrence of these factors is determined. The factors that occur most frequently are the high use of appliances, low design quality of batteries, and lack of technicians. These factors are identified and validated in the case study and are generalised to micro-grids in rural developing areas. This is because these factors are the most commonly identified in the literature review with different micro-grid areas.

It is recommended to limit the impact of battery performance on micro-grids, as this is the most relevant factor in rural developing areas. This factor has a direct impact on the electricity availability of the micro-grid, especially in the evening.

SQ 4: *What is the current performance status of micro-grids in rural developing areas?*

Rural developing areas often experience different seasons. For micro-grids in rural developing areas, seasonal variation significantly impacts their performance, with differences in terms of electricity availability between the dry and rainy seasons. Therefore, it is recommended to analyse the various seasons in the rural developing areas to find out the performance status.

In micro-grids with optimal battery performance, both seasons meet the system performance requirements. Indicating proper system size at the beginning of the developed system. However, ensuring the daily system requirement of no more than 8 LOLE hours per day is more challenging than meeting the evening requirement of no more than 8 LOLE hours in the evening. The rainy season in developing countries is the critical season due to insufficient electricity generation of solar panels. In the case study the battery struggles from almost the beginning with the daily system requirement in the rainy season. In the dry season, performance requirements can easily be met. In dry seasons with more hours of sunshine, the storage capacity is often the constraint. In the case study, the battery's State of Charge (SoC) frequently reaches its maximum battery capacity.

SQ 5: *What is the impact of the battery performance on the performance of micro-grids in rural developing areas?*

The battery performance is identified as the most relevant factor, making it essential to analyse its impact. The battery performance has an impact on the availability of electricity on micro-grids in rural developing areas. Batteries that operate in high-temperature climates have a shorter life expectancy, which is the case in most developing countries. The average lifetime when the battery is no longer functioning is half of its expected life under developing country conditions.

At a certain battery performance level the system requirements can not be met. The electricity availability decreases as the battery performance decreases, with notable differences between the dry and rainy seasons. For electricity during the day, the availability of electricity issues starts earlier in the rainy season than in the dry season. The rainy season is the limiting season and determines the lifetime at which battery replacement is recommended.

SQ 6: *What are possible mitigation strategies within the rural developing context and what is the impact of these strategies on micro-grids in rural developing areas?*

It is recommended to select mitigation strategies in line with the area's environmental, regulatory and economic conditions, ensuring they are suitable for developing context. Possible mitigation strategies that fits in this context and focus on battery performance are demand control (DC), battery capacity increase, and the use of air conditioning.

Air conditioning decreases the overall availability of electricity in both seasons and therefore negatively affects the minimum performance level of the battery. This means that even at higher battery performance levels, the battery cannot meet the system requirements. Leading to no mitigation of the impact of the battery performance on micro-grids performance. In the rainy season, air conditioning ensures that system requirements are exceeded from the beginning. Air conditioning extends the batteries lifetime, since cooling reduce the degradation rate of batteries. This is useful in the dry season, but in the rainy season, this lifetime extension has no helpful effect as from the start the system requirements are already exceeded.

DC mitigates the impact of the battery performance on micro-grids performance in the evening. It has a positive impact on the minimum battery performance level in both seasons to meet the evening requirement, it is the only strategy that actually increases the electricity availability in the evening. Considering the daily requirement, DC has a negative impact on the electricity availability in both seasons. Thus not mitigating the impact. This is because the demand-controlled hours result in more hours without electricity, independent of battery performance. However, implementing this is the most costly. DC has a minor negative impact on the recommended battery replacement lifetime. The battery lifetime when exceeding system requirements is shorter compared to other strategies.

The increase in storage capacity has a positive impact on the minimum battery performance level in both seasons. In addition, battery storage has a positive impact on the batteries lifetime in both seasons. Now that the answers to all the sub-questions is formulated, the main research question can be addressed.

> ***Which factors impact the performance of micro-grids in rural developing areas, and which mitigation strategies can improve the access to electricity?***

The battery performance impact the performance in terms of electricity availability in rural developing areas. Mitigation strategies can mitigate this impact on the performance and improve the access to electricity. It is recommended to apply a mitigation strategy targeting the season that faces the greatest challenges regarding electricity availability. In many developing areas, this is the rainy season due to limited sunlight. Therefore, the first mitigation strategy should focus on the rainy season, aiming to reduce the impact of battery performance on the availability of electricity. In addition, interaction with users is recommended to determine system requirements. The system should first focus on electricity in the evening hours, as this is the desired system requirement.

Demand Control is considered the mitigation strategy that can address electricity availability problems related to battery performance issues within the current economic, technical and regulatory environment of micro-grids. DC is effective because it positively affects the electricity availability in two ways. It decreases the minimal battery performance level and it increase the electricity availability in evening hours, enhancing access to electricity in rural areas. DC is needed from a certain battery performance level to extend the system performance, but it is recommended to implement DC from the beginning as this increases the evening hours with electricity. Even if financial resources are available, DC remains an attractive strategy for providing electricity in the evening hours. However, to increase daytime electricity availability and extend the actual battery lifetime, adding storage is a recommended strategy, but realising this involves more costs. The capacity of deployed micro-grids in rural developing areas is too small to add air conditioning loads and therefore to use air conditioning effectively. This mitigation strategy is not recommended within the current environment.

It is recommended to implement this strategy to ensure the availability of the micro-grids in rural developing areas to ultimately increase the access to electricity.

11
Discussion

While this study aims to provide a comprehensive approach the micro-grid systems in rural developing areas, it is important to discuss the results, compare the research with other literature and discuss the limitations transparently. This is to demonstrate its contribution to scientific and social research.

11.1. Interpretation of results

This research aims to contribute to scientific studies in the field of rural electrification. Ultimately, improving rural electrification enhances living standards and supports economic development in these areas. This research achieves this by developing a comprehensive approach that identifies, simulates, analyses, and mitigates external factors and their impact on the performance of micro-grids in rural developing areas.

The conclusion of this research is based on a single case study in Sierra Leone. The results of the case study are interpreted in a way that generalises them to all micro-grids in rural developing areas. The research concludes that batteries have a significant impact on the functioning of micro-grids, and therefore, the effects of this should be limited in already developed micro-grids. This can be achieved through demand control and the addition of extra storage capacity.

However, giving advice for all micro-grids based on one micro-grid is limited but not entirely unreasonable. In general, the results are applicable to most rural micro-grids in developing areas. This is because the study first draws on a wide range of literature from different parts of the developing world to broaden the focus. This broad focus is then made more specific through validations from the case study. Additionally, most of these micro-grids face similar seasonal impacts, such as periods with high temperatures and a lot of sunlight and cooler periods [88]. In addition, rural developing micro-grids also face economic constraints and are difficult to access.

If this research is conducted in other rural developing areas, field research remains crucial. Field research helps to identify user needs as specifically as possible and determine common factors which influence that particular micro-grid. It is recommended to collect extensive technical data. The more available technical data, the more realistically the micro-grid model can be developed and simulated.

11.2. Comparison with Existing Research

This research provides a more comprehensive analysis of the potential factors influencing the performance of micro-grids. The study by Numminen et al., Nuru et al., and Ngowi et al. examines factors affecting an installed micro-grid [16], [28], [27]. The factors identified in their study align with those found in this research. However, this study offers a broader overview of possible factors that could impact micro-grid performance. This research also takes a different approach to analysing potential factors. While the mentioned research also identifies factors influencing micro-grid performance through case studies, their methods differ. In these studies, the factors are derived solely from case studies, whereas this research first establishes a list of potential factors through a literature review. These factors are then validated through the case study. This approach provides a new method for identifying influencing factors.

Furthermore, this research extends the existing literature by incorporating a simulation-based model. Model studies of existing micro-grids in the literature review used mostly optimisation models [25], [26], [32]. Only Wassie et al. used a simulation model [10]. It also expands the existing literature by introducing mitigation strategies in a rural context. It explores how to mitigate the impact of the battery performance through a simulation study. This is an extension of the model studies by Wassie et al., Zebra et al., and Bukari et al., which primarily identify influencing factors without mitigation strategies [10], [25], [26].

The findings of this study also align with existing literature. Batteries are identified as the most relevant factor in this research. This research shows that the high temperature at the micro-grid site negatively impacts battery performance and lifetime. Wassie et al. confirm this, noting that accounting for local weather conditions is essential for improving micro-grid performance [10]. Kapole et al. also identified batteries as a specific issue [29], and Bukari et al. observed that the batteries in their case study had reached their terminal point [26]. This validates the relevance of the factors identified in this research. Additionally, the actor analysis reveals that the economic environment, particularly the tariff structure, is not able to cover operational and maintenance costs. Zebra et al. mentioned that favourable tariffs are only achievable with government subsidies [25]. Furthermore, Bukari et al. confirm this, stating that the cost of electricity supply in the case studied micro-grid was higher than the current tariffs. Therefore, it is impossible to recover operation and maintenance costs. This could further worsen performance issues [26].

11.3. Limitations

11.3.1. Social-technical system limitations

The exploration of the socio-technical system is based on a case study involving observations and interviews with community members and experts in Sierra Leone. A limitation that affects data interpretation and the loss of data is the language barrier. A translator is employed during interviews, and this can lead to information loss during translation. Additionally, the limited knowledge of some interviewees about the system results in misunderstandings or incorrect responses. Although misinterpreted answers are excluded from the analysis, certain errors may be missed which can influence the outcomes. To mitigate this, a larger number of interviews helps filter out inaccurate responses more effectively. Another issue noted in the subject of interviews is that interviewees are not always completely truthful or provide distorted information. Answers are given out of self-interest. For example, operators report that the micro-grids rarely experience electricity outages, while community members indicate that blackouts are frequent.

In addition, a stakeholder analysis is conducted through interviews with key stakeholders, although direct interviews with government representatives are not obtained. Including government interviews could provide a better understanding of the actor situation and the system context.

The case study is based on four communities, with a total of 27 interviews. The literature review identifies several factors affecting the performance of micro-grids, and these are validated in the case study. The probability of occurrence of certain factors is derived from these four communities. The quality of the research improves when considering more communities. These limitations may affect the actor situation or the selected relevant factors.

11.3.2. Model Limitations

Many technical input variables are based on literature, due to a lack of site specific data. The outcome of the model is highly dependent on local design choices for the distribution and generation of assets. Small micro-grids, like those in this study, can be sensitive to transmission and conversion losses, which can significantly impact the KPIs. A simplification in the model is that inverters, which convert Direct Current (DC) to Alternating Current (AC), are not included in the model due to a lack of available data. As a result, conversion losses are underestimated, which can lead to an overestimation of the results, resulting in a model with possibly more available electricity than in reality. Although this affects the accuracy, it is less problematic for the final outcomes. This is because the study focuses on comparing the system behaviour across different mitigation strategies.

Additionally, the battery configuration in the model is simplified to a single large battery, whereas the micro-grids in the case study consist of multiple 2 kWh batteries. Since these batteries are of the same type, located in the same place, and operating under the same conditions, the differences between the model and reality are minimal. This simplification mainly affects maintenance strategies, as the model assumes that the battery degrades as a whole, whereas, in practice, individual cells or batteries may be replaced.

Furthermore, costs were included in the selection of mitigation strategies. However, the SDG7 goal focuses on sustainable, affordable, and reliable energy to increase access to electricity for all. The reliability aspect aligns with this objective. To provide a more comprehensive evaluation of micro-grid performance, future research should incorporate all cost factors to identify the best mitigation strategies. In addition, the influence of the mitigation strategy on the cost of electricity, whether this strategy ultimately has a positive or negative effect on the operator's revenue. This in the end assesses whether this can enhance the affordability and sustainability of micro-grids.

Finally, when modelling the average electricity availability in LOLE hours, only hours of system overloads are considered as no electricity hours. Although capacity constraints and transmission losses were accounted for, other factors that cause performance issues are not included. Voltage collapse or frequency deviation can also cause performance problems and are not included in this study. As a result, the average power availability in this study may be higher. Further research could include frequency deviation and voltage collapse to provide a more accurate analysis of system performance.

11.3.3. Data Limitations

The available data contains a load profile for only one day, which is applied to all days, without distinguishing between weekdays and weekends. The electricity demand may differ on weekends, this may affect the model's accuracy and the availability of electricity. In addition, the model runs for two months per season, since the generation profiles are based on two months in the rainy season and two months in the dry season. To extend this research it is recommended to use several load profiles, load days and longer runs.

A crucial factor that affects the lifespan of the battery is the fade curve used. While validation shows that the chosen fade curve generates results comparable to the actual lifetimes of batteries in Sierra Leone, using a different fade curve could lead to different lifetime outcomes. This research assumes a temperature of 45 degrees Celsius, which directly impacts the lifespan of the battery. In reality, there is a temperature variation in Sierra Leone between the dry and rainy seasons. This may have a greater influence on the KPI lifetime of the battery between these seasons. Other factors that influence the lifetime of the battery are implicitly included in the fade curve but are not tailored to the specific conditions in Sierra Leone. For a more accurate study, it is recommended to take more into account the current conditions and influences that can affect battery ageing. For example, temperature differences in other seasons and the State of Charge (SoC) of the battery, as this also affects the degradation rate of the battery.

11.4. Further research

Now that Demand Control (DC) is identified as a potential strategy to address battery performance issues, this strategy is reconsidered within the context of the system to determine its feasibility in developing countries. Firstly, it meets the requirements of the financial environment; low cost and the absence of government support. This makes sense since the strategies are selected based on these criteria. Implementing DC in micro-grids within developing countries requires organisational adjustments for micro-grid operators to turn the micro-grid off and on. It requires minor adjustments which fit well the technical environment in the context of developing countries. This strategy can be managed centrally as there is no need for cooperation based on user regulation. It is the responsibility of the grid operator to switch off electricity for a certain number of hours each day. This strategy does not allow system users to use electricity during demand-controlled hours. In the Western world, this is not accepted due to high expectations for constant electricity access and consumer autonomy. However, in developing countries, this may be different. DC strategies are more feasible because of the already low user expectations, frequent performance issues, the limited alternatives and because users value some form of available electricity. However clear communication of DC schedules is essential. Information lectures can be given to educate users about DC and inform users about the effect and demand-controlled hours to manage expectations and avoid confusion.

While these are the reasons why DC could work in rural development areas, the question remains whether DC is desirable for users. Further research is therefore needed on DC. It is recommended to investigate whether demand-controlled hours are desirable compared to the current micro-grid operation.

In addition, further research is recommended to implement this strategy in practice and examine both its technical and social outcomes. Technically, it is important to verify whether the strategy works as effectively in practice as it does in the simulated model. Socially, the research should assess whether the strategy is feasible for grid operators and ensures user satisfaction. Moreover, further development of DC strategies is needed to determine the optimal timing and duration of demand control hours. Besides that, more DC configurations could be included, such as turning off parts of the micro-grid to see if this in the end improves micro-grid performance. Future research could also apply DC to other relevant influencing factors, such as the high use of appliances, to analyse whether DC enables the use of higher-load devices. Lastly, the combination of mitigation strategies can enhance the performance of micro-grids in rural developing areas, but further research is needed to prove this.

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A

Semi-Structures interviews

This appendix consists of the themes and summaries of the semi-structured interviews in the communities and with experts.

A.1. Semi-structured interview subjects

In the interaction with stakeholder semi-structured interviews are conducted. The interview subjects were based on the factors identified in chapter 5.

Social

- The use of the system
- Appliances and usage
- Community behavior

Technical

- Technical characteristics
- Micro-grid failures
- Performance issues
- Maintenance procedures
- Weather conditions

A.2. Interviews

A summary of the semi-structured interviews in the interaction with stakeholders is given below. The interviews are ordered per community.

A.2.1. Community 1

1. **Community Agent**

    Tasks

    - The role of this community agent is the link between the community and the grid operator. The agent is the first point of contact for any issues that arise. Should any problems occur, community members can be reported to the agent. The agent is responsible for carrying out minor operational and maintenance tasks, like cleaning the solar panels and checking for errors in the system. Finally, the agent sells top-up to households connected to the micro-grid.

    Technical information

- The PV panels generate electricity, which is then transferred via an inverter to the batteries. The batteries then transfer the electricity to the grid.
- The grid is comprised of three principal lines, which serve to enhance reliability to a slight degree. In the event of a failure in one of the lines, the other component of the community can still obtain electricity.
- He said electricity is shared equally among the community, power hours are not shared among the three transmission lines.
- Some PV panels are connected to the battery, while a proportion is connected directly to the inverter. The agent was unable to provide the percentage of the distribution.

Technical knowledge

- The community agent acknowledges a lack of expertise regarding the electricity grid.
- The agent is able to perform basic operational tasks. He had one training that trained him how to turn on and off the grid, fix technical issues and what to do if the battery refuse to charge.
- The agent does maintenance activities 3 times a year. The agent is aware that the PV panels have a significantly higher output after cleaning, but the agent doesn't clean it more than three times. It is inconvenient because the current design has placed the solar panels at a considerable height.
- Comprehensive knowledge of how the system works is lacking. When such failures occur, an operator from Freetown must be called to solve the problem, which can take several days.
- The agent wants to become a technician, but the operator does not offer that opportunity.

Communication

- Communication between the community and the agent is by word of mouth and through a community WhatsApp group. In this WhatsApp group, the agent can let several people know at once if something is going on. The three main topics in the WhatsApp group are about the top-up for the meters, failure of meters and lighting problems.
- The agent does not have frequent meetings with the operator, only when there are failures. He had a meeting once, but that was the training.
- The agent mention that the relation between him and the operator is good, but he wants more sallery.

Grid performance and reliability

- The agent indicated that the electricity is perfectly operational from 10 a.m. to 11 p.m. without interruption.
- The community agent reports that the grid generally works perfectly, with no failures or theft. They assert that theft is impossible with the current grid construction.
- However, the community agent highlights a significant issue: the lack of light in the evening. This problem is attributed to weak batteries, which cannot store electricity for extended periods, preventing the use of light during the dark hours.

Barriers and challenges

- The agent highlights a significant issue: the lack of light in the evening. This problem is attributed to weak batteries, which cannot store electricity for extended periods, preventing the use of light during the dark hours.
- The agent mentioned scale-up challenges, as the community consist of more than 8000 houses and only 200 ar connected. No more is possible and even now has no electricity in the night.

- A recent incident involved a fire in one of the cables, which was caused by lightning. The electrical power supply was unavailable for one week. Long ago there was a fire in another smaller cable due to overheating, which resulted in a day without electricity.
- The community agent asserts that theft is impossible with the current grid construction.
- The lack of technical knowledge leads to long repair times, as he has to call the grid operator and the grid operator has to send an technician from Free Town
- Sometimes transmission lines are used as washing lines and plastic sticks to the lines, people hang it off and that causes damage
- Earthcables break down sometimes, which may increase the risk of getting damaged during lightning

Improvements

- The biggest problem identified is the weak batteries, which cannot save electricity for long durations, resulting in no light during the evening. Improvements in battery storage capacity are needed to ensure consistent light availability during dark hours.
- Increase of solar panels, the capacity is not enough for the community and the appliances they want to use.
- The agent wants another payment system. The agent buys the top-up for the community from the operator, after the activity the agent can sell it to the community. The agent does not have enough money to pay in advance, so there is always short of electricity. The operator does not trust the agent, so payment has to be made in advance. Moreover, the community does not want to pay upfront. So the agent is the middleman.
- A display on the meter to see the availability of electricity, to create more trust and efficiency.

2. **Community Health Centre**

Appliances and usage

- The nurse states that grid electricity is used solely to provide light.
- If the grid allows, the nurse wants more lights and electric fans

Communication

- The nurse does not mention the operator directly but implies a lack of adequate response to the reliability issues, indicating a need for better management or infrastructure improvements to ensure a consistent power supply.

Grid performance and reliability

- The presence of a health centre is one of the selection criteria for the implementation of micro-grids. Therefore, a micro-grid is built in this community. In that case, the nurse mentioned that it is annoying that the electricity is not reliable, as this grid is specially built for this clinic. The Health Centre recalls that the electricity was reliable initially, but now the service is poor, particularly in the evenings when there is no light, making it difficult to assist pregnant women giving birth.
- The nurse from the Community Health Centre expresses frustration with the mini-grid, noting that they have been without electricity for two days. She is aware that they are not required to pay for the electricity, but the lack of reliable electricity makes the work conditions challenging.

Challenges and barriers

- The Health Clinic has a freezer, though it is not connected to the grid. Instead, it has its own generator. The grid is not reliable enough for cooling vaccines.
- The nurse indicates that the increased number of people connected to the mini-grid decrease the reliability. She thinks that fewer connections would improve the situation.

Improvements

- The nurse mentions that a freezer for vaccines is kept off the mini-grid because the grid's reliability issues could compromise the storage of vaccines. The nurse highlights the importance of reliable electricity for critical services and expresses a desire for a better mini-grid.
- She suggests that the mini-grid should be modified to ensure evening lighting and allow the use of fans and freezers during the day. They believe that priority should be given to essential services over general lighting needs.

3. **Business Owner 1**

   Appliances and usage

   - The business owner uses a fan and light with the electricity from the mini-grid

   Technical knowledge

   - The business owner do not have a clear understanding of the cause of the interruptions and feel that they should receive the electricity they are paying for.

   Grid performance and reliability

   - The business owner states that the electricity is not reliable, particularly at night. They often do not have power during the night.
   - During the day, the electricity supply is generally better and sometimes intermittent. Sometimes one or two short blackouts. The business owner mentions that their light is currently on.
   - However, when real blackouts occur, they can last up to three days.

   Barriers and challenges

   - The business owner is unsure of the blackouts' reasons, noting that sometimes there is a loosely hanging transmission line. He mentioned a single incident where a fire was caused by lightning, but this happened a long time ago.
   - The business owner also mentions that the solar panels can become dusty, which might affect performance, but cleaning them is challenging because they are positioned high up and he does not she the agent clearing the panels often
   - The business owner believes that theft of electricity is impossible with the current setup.

4. **Business owner 2**

   Appliances and usage

   - The business owner uses three freezers, a speaker, and light with the electricity from the mini-grid.

   Technical knowledge

   - The business owner is unsure of the exact causes of the electricity issues, he is just focused on having electricity.

   Grid performance and reliability

   - The business state the grid is reliable during the day, but he mentioned the reliability problems at night.
   - On Thursdays and Fridays, when the market is active, the electricity becomes unreliable. On market days, the electricity often runs out quickly and does not come back on, causing cooling issues for the business owner. To ensure the freezers have power, the business owner starts cooling items before Thursday, as the electricity supply is more stable earlier in the week.

   Barriers and challenges

   - The business owner observes that people hang items like clothes, on the transmission lines.

- He mentioned that the solar panels are out of sight, so he does not know if dust affects performance.
- All the freezers on the market days causes blackouts

Improvements

- The business owner expresses a need for a more reliable grid, especially when more people use freezers.
- He highlights the importance of having electricity at night and expressed concern that the hospital also lacks reliable electricity, which is particularly troubling since the grid was installed to support the hospital.

5. **Household 1**

Appliances and usage

- Only 2 light bulbs are connected to the micro-grid.

Technical information

- The household member acknowledges that the grid operator tries his best but lacks knowledge about the grid issues. The operator has informed the community that no more connections are possible.
- The member feels that the operator sometimes listens but lacks knowledge about the grid's issues. But not that much happens, or takes a long time. When asked about the power interruptions, the operator often does not have answers.

Grid performance and reliability

- A member of the household experiences inconsistent access to electricity, with neighbours sometimes receiving power an hour earlier. The reason for this discrepancy is unclear.
- The household member reports that electricity is generally available during the day, but at night they often have only about one hour of power. This inconsistency affects the children's ability to study, as they go to school or work on the land during the day.

Barriers and Challenges

- The member thinks the weak reliability is because of the lack of working batteries.

Improvements

- The household relies on solar torches for light in the evening, which are inconvenient because they must be held. This limitation forces the family to align their activities with daylight, sleeping after dark and waking early with the sun.
- The household member suggests the need for more reliable nighttime electricity to allow children to study and improve their overall quality of life.

6. **Household 2**

Appliances and usage

- The household has a fridge, fan, TV, charges phones and have 5 light bulbs.
- They uses the fridge 3 hours a day, phone charging 1 hour a day and fan and light only in the evenings.
- The household consist of two members, but share the meter with one other family consisting of 4 members.

Technical knowledge

- The member thinks the grid does not perform in the evening because of the batteries.
- The family switch off the light when leaving the house.

Communication

- The member mentioned that the agent is a good man. For the communication with the agent there is a WhatsApp group, but she wants to speak in person with him.
- There is no contact with the grid operator.

Grid performance and reliability

- A member of the household experiences light from 10 or 11 a.m till 8 p.m.
- When the grid was designed the electricity was reliable and after that the reliability decreased.
- One day before the market starts the grid is more unreliable.
- Last week, the power failed for 2 days, the agent could not give a reason why this happened.

Barriers and challenges

- The member mentioned that the top-up they buy is dropping fast because the bulbs they use are not efficient and that costs a lot of top-up.
- The high voltage and power appliances are the reason for the black-outs and no power in the evening.
- Last week there was a broken cable near the hospital due to fire, that was fixed in one week.
- The member lives next to the PV panels and she has not seen any cleaning activity for the last half a year.
- The member mentioned that the agent has a lack of knowledge and can help with electricity issues and it takes hours or days to fix it.
- Theft is impossible and have not heard about it in the community.

Improvements

- Change the top-up system, so the family can buy top-up when it is needed and to have to buy from the agent.
- Add more panels to everyone can use more appliances.

7. **Household 3**

Appliances and usage

- The household uses electricity to charge phones, and has 4 light bulbs.
- They share the meter with 2 other families, with a total of 9 people.

Technical knowledge

- The family has no idea what the reason is for the electricity blackouts.
- They turn-off the light when they leave the house, because the top-up is expensive.
- The agent never explains how the electricity grid should be used. They don't know that they have to turn off the electricity during lightning.

Communication

- They stated that the agents listen to them and helps.
- When the grid was design, the designer ask a few questions. The question was whether they would use light when they created an electricity system.

Grid performance and reliability

- The grid is operating from 10 a.m.till 8 p.m.and they are satisfied with the electrcity.

Barriers and challenges

- Once there was a fire near the hospital.
- They have not seen any sticks on the cables

- They know that the agents cleans the solar panels
- Draining power illegally is not possible
- The pole in front of their house broke down and the agent replaced it with a new wooden pole.

Improvements

- They want to have a freezer, but the grid is too expensive.

A.2.2. Community 2

1. **The agents**

Tasks

- The community has four agents in total. Two agents are responsible for the repair tasks and the others for the maintenance tasks in terms of cleaning.
- They are tasked with cleaning the batteries and PV panels, checking the inverters, fixing any problems and calling the main operator if anything is broken.

Technical information

- The grid has above 800 connections including 6 school and a Community Health Centre.
- Only around 150 connection get electricity
- The system consistis of 360 batteries with 2 Volt and 1000 Ah
- The grid has 4 transformers. The transformers are located near the power house where the PV panels are placed. They convert the electricity from 400 volts to 220 volts.
- The system has a generator, but it is not in use due to the high price of oil.

Technical knowledge

- After being trained by Power Leon, they know how to repair broken meters and how to clean the batteries and PV panels.
- The maintenance protocol consists of cleaning the PV panels and batteries, this happends three times a week. They also check transmission lines and pole.
- They do not disconnect the batteries when they are fully charged. The electricity from the solar panels goes through the batteries to the inverter and then to the grid.
- The agents do not turn the grid off during rain, storms or lightning.

Communication

- The stated that the relation with the grid operator is good.
- They do not have meetings with the operators, only when something breaks or other problems arise.
- If there is a big problem with the system, they tell the community chief and the community chief informs the rest of the community.
- They have not told the community how to use the electricity, only how to buy electricity.

Grid performance and reliability

- There is electricity from 9-10 a.m. until 8-9 p.m.
- Between these hours the grid performs well, but sometimes the batteries are switched off because of the heat. This causes blackouts.
- Houses who are are connected in the right part of the grid, the grid is reliable, but people living in the other part have had no power for the last 6 months.

Barriers and challenges

- The stated that during raining season rain affects the transmission lines. The rain damages the lines and the water on the cable becomes hot, causing fire. This happens in two areas of the electricity grid, leaving these areas without electricity for months. The grid operator is not repairing it because the grid operator say the grid funder is responsible for that. A fire in a cable occurs every 2 or 3 months.
- The batteries become too hot and must be switched off. This leads to no electricity between 4 and 6 p.m.
- The agents mentioned that the freezers use too much electricity, causing high peaks that the grid cannot deal with.
- Theft happens, but they catch the thieves quickly because everyone in the community knows everything. But the power house is secured 24h because people from outside the community wants to steal system components as batteries.

Improvements

- Want want the the grid is more sustainable in the future, we need expansion of everything. The PV and battery capacity is too low for this community.

2. **Household 1**

Appliances and usage

- The household primarily uses their electricity for charging phones and lighting.

Technical knowledge

- The community agent sometimes cleans the PV panels, mostly in dry season. They think once a month.

Grid performance and reliability

- The operational hours of the grid are from 10 a.m. till 9 p.m.
- The household reports that during the day, they have access to light without issues. However, they rely on a generator as a backup system, primarily running from 8 p.m.to 11 p.m.for lighting purposes

Barriers and challenges

- The household mentions using the transmission lines for hanging clothes but highlights security concerns.
- Break-ins at the powerhouse have occurred, primarily targeting batteries. As a result, access to the powerhouse is restricted, requiring oversight from the operator.
- The household resides further away from the main community area, the reason why they don't know if there are other reasons for interruption

3. **Household 2 including a business**

Appliances and usage

- The household consists of two persons and she uses the meter with 6 other people.
- The household uses electricity for 3 light bulbs and to charge phones. The household also has a small shop and uses the freezer to sell cold products. The member explains that it takes about 3 days to turn water into ice because the freezer cannot be used at the highest level. This causes a short circuit. The member uses the profit for buying new top-up.

Technical knowledge

- She switches off the electricity before she leaves because it is too expensive and the light bulbs are not efficient.

Communication

  - If there is something wrong she needs to find the agent. There are no community meetings and she mentioned that there is not a WhatsApp group which she can use.
  - The member does not trust the agents and the agents fix it or they give the excuse to the network operator if something is broken and not fixed.

  Grid performance and reliability

  - The grid is reliable during the day, but many times the grid turns off around 4 p.m. and goes on again between 7 p.m. The family member do not know the reason for that.
  - She mentioned that she keeps buying electricity because she can not live without anymore, she is used to it. According to her, she is stuck because she can no longer do without electricity, as she is now used to it.

  Barriers and challenges

  - The family member has not seen broken lines, theft or fire.
  - She knows that the agents cleans the PV panels.
  - She finds that the electricity she buys runs out too quickly. Sometimes she has to buy electricity after 2 weeks and sometimes after 1 week, while she has the same consumption pattern.

  Improvements

  - She wants electricity for 24 hours a day.
  - More efficient lightning, to decrease her electricity use.
  - She wants to know her consumption pattern to know how much electricity she needs to buy.

4. **Business 1**

  Appliances and usage

  - The business uses electricity for two lights, a fan, and a freezer.

  Grid performance and reliability

  - The business reports having electricity during the day but experiencing outages at night, typically around 8 or 9 pm.

  Barriers and challenges

  - Blackouts during the day are also mentioned, lasting a few hours. These interruptions are suspected to be caused by line issues, potentially leading to disconnections when lines break down.
  - These blackouts are also attributed to battery issues.

5. **Business 2**

  Appliances and usage

  - The shop has 5 playing machines and two lights. The business owner relies on playing machines connected to the micro-grid for income. These machines have batteries as backup, ensuring they are operational even when the micro-grid is not functioning optimally.

  Grid performance and reliability

  - While electricity is generally fine during the day, there is no electricity in the evening. Some days there is no electricity because it is too cloudy.

  Barriers and challenges

  - The business experiences line issues occasionally, with loose lines observed.
  - People with freezers are also a problem because they use all the electricity during the day. This means that the batteries cannot be changed and when it gets dark the batteries are empty.

6. **Business 3**

   Appliances and usage

   - This business is a sports bar, offers customers the opportunity to watch football matches. It charges an entrance fee, which is used to purchase more electricity. The bar has two televisions and five lamps for lighting, all connected to the mini-grid. They use a generator as back-up to ensure the visitors can watch the football match without black-outs.

   Grid performance and reliability

   - Electricity is generally reliable during the day, with occasional short blackouts. However, problems arise in the evening. The generator runs for extended hours into the night to compensate for grid failures, this to watch the football matches uninterrupted.

   Barriers and challenges

   - The interviewee highlighted concerns about the reliability of the grid infrastructure, pointing out weak poles and loose lines that contribute to the unreliable electricity supply.

A.2.3. Community 3

1. **Community Chief**

   Tasks

   – The Community Chief is the head of the community and has the highest power. The Chief makes decisions, leads meetings and enforces laws.

   – The chief is also the point of contact for people outside the community and interacts with the government and NGOs.

   Appliances and usage

   – The community leader reports that 80-90% of the community is connected to the grid.. There are a total of 8 freezers in the town, which are used for cooling water. He mentioned that the community can no longer live without the freezers and that the number of freezers will increase in the future, as the freezers are a source of income for community members.

   Communication

   – The community chief expresses his dissatisfaction with the network operator. Nothing has been done since the problems started.

   – Additionally, there are complaints about the payment system, where users are charged for every minute of solar electricity, even when lights are switched off. This policy has led some users to disconnect from the grid.

   Grid performance and reliability

   – The community faces challenges with access to electricity. The biggest problem is no light during night time, with no electricity from 7 or 9 p.m. until the late morning, around 10-11 am. After 10-11 a.m. there is electricity. The chief mentioned that no light during the nights is disrupting activities and essential services

   – The chief blames these problems on the micro-grid. Stated that the batteries are weak, and the system can't handle all the appliances, like freezers. Back in the days, the electricity was 24 hours available, but now it's not reliable.

   – In the rainy season,limited sunlight during this period also affects the electricity output.

   Barriers and challenges

   – The batteries are weak, this is according to him the reason they don't have electricity during the night.

- The other problem is the number of freezers. The number of freezers drains the batteries. The chief thinks that during the day there is not much electricity to charge the batteries with because the freezers use all the electricity.
- And they need more capacity

2. **Household 1 including a business**

Appliances and usage

- The household uses the mains connection for a freezer, to charge phones and they have two light bulbs. They use one bulb that is connected to the grid and the other is no longer connected. As the grid often fails, they use a solar set to light the mother's room.
- The freezer is always on when there is electricity to cool beer and soft drinks to sell to others, the phone is charged for 2 hours a day.
- They mentioned that they don't have a choice whenever they want to use the appliances. The available electricity makes the decision.
- Despite the desire for improved lighting, financial constraints limit the household's ability to invest in alternative solutions such as solar lamps.
- They only stay connected because of the freezer. The freezer is the income. If there are a lot of power cuts or the electricity is running out, they raise the price of cold drinks. This is the way to generate income.

Communication

- They are not satisfied with the grid operators an do not trust them. The operator made promises during the grid's development, such as income generation and freezer loans, but they were not kept. Their emotions are expressed in disappointment and distrust.
- A lamp no longer functions due to a damaged cable. Despite informing the operator about the issue, no action has been taken to repair it. He mentioned that he doesn't need light during the day, and at night he wants it, but there is no light, so he feels there is no point in talking to the operator.
- This system has led to frustrations and to disconnections in the whole community.

Grid performance and reliability

- The grid is not reliable in their opinion. Electricity typically switches on around 11 a.m. and switches off between 7 or 8 p.m. Most of the time they only have an hour of electricity at night.
- A family member demonstrates how to trigger a blackout in his home. When he puts the fridge on the highest level, the meter switches off. He thinks it has something to do with the current, this is why he only uses the freezer on level 5.

Barriers and challenges

- Limited electricity access affects daily activities, such as studying at night.
- The family member never sees strange things about the grid, the grid works. Broken transmission lines are not observed. Only the batteries are not working and are the reason for no light.
- The operator does not come that often to clean PV panels. they see him once a month, but not always cleaning.
- There are too many freezers.
- Theft is not possible, the operator is checking every one or two months.
- The community faces challenges during the dry season due to dusty solar panels and infrequent cleaning visits, the operator comes maybe once or twice a month.
- They are frustrated about the inefficiencies of the top-up payment system. The system charges connected households regardless of usage. Since this is noticed, the family keeps their freezer running continuously as they are charged anyways. This paying

system leads to disconnections by other users. Moreover, even without purchasing new top-ups, charges continue to accrue, resulting in fines that must be paid, regardless of usage.

Improvements

- The family feels that the grid was not designed to meet their needs and usage. They need electricity during the night and that is what not works. Questions where asked before the developed of the micro-grid, but the familiy had not idea.
- The household desires to have lighting available from 7 p.m.to 12 a.m. to facilitate nighttime studying. Now the family goes to bed when it is dark, as darkness makes the evening hours unproductive. They have a torch, which is cheap but not practical as you have to hold it.
- If nothing improves more and more people will disconnect in the future. If the family saves money they can buy their own solar lamps and even more. However, at this time, there is no financial resource available.

3. **Household 2**

Appliances and usage

- The household use the grid connection to charge their phones. A light bulb is connected but is not in use, because they do not need light during the day.
- They used to have a TV, DVD player, but since the grid became unreliable, they do not longer use these appliances. Our TV viewing was confined to the evenings and Sundays, but the TV is sold.
- If electricity becomes more reliable the priority is to have access to a fan and a freezer.
- They continue to purchase top-ups for charging their phones, they still believe that the situation will eventually improve. If they don't buy top-ups, within one or two months could result in the removal of their meter.

Community

- The family member does not trust the operator as he accuses the operator of stealing their money.
- If something is broken it won't be fixed, but they still want to stay connected in case it the improve the grid.
- The grid operators promised us constant access to light and a freezer, but they still have not received any of these promises. The power grid changed our lives by allowing nightly study sessions for our children, but they are back to unreliable electricity supply.
- The family have still faith that the operator will repair broken meters and install new batteries, even after five year.

Grid performance and reliability

- The grid's performance is weak in their opinion. There is electricity starting from 9:30 or 11 a.m. and switches off at 8 p.m. They experience disruptions and do not have access to 24-hour electricity. There is no electricity in the dark and that is the most important.

Barriers and challenges

- The biggest problem seems to be batteries, which affect the reliability of the power grid
- There are no observed broken transmission lines, there was a single incident where lightning caused a fire in the grid.
- The operator comes by every one or two months and goes to the power house. The operators only focused on maintaining the powerhouse without addressing other critical issues as batteries, besides that they clean the PV panels around every 2.
- The family member is sure there is no electricity theft because we are one community. According to him, only the grid operators steal their payments.

Improvements

- They want light in the night and they think new batteries are the solution.
- They want a different payment system where they only have to pay when they use electricity, not when it is produced.

4. **Community Health Centre**

Appliances and usage

- The health centre has been connected to the mini-grid since the start of the project, as it was initiated specifically for them. However, due to the unreliability of the grid, they only use the electricity for a fan and can not rely on it for their freezer.
- They have solar panels from another organization, which they use to power the freezer.

Communication

- The power operator is not reliable, despite promises made a year ago to replace the batteries.
- They say UNOPS is responsible, but we don't hear from them either

Grid performance and reliability

- The grid performance is weak. UNOPS stated that they had funds allocated for maintenance, but no action has been taken. With this grid performance, they can not run the community healthcare clinic.
- On cloudy days, the electricity supply is worse. There is less available electricity.

Improvements

- The doctors stated that the grid is not effective at all. They need a reliable grid and also for the evenings, as childbirth without light is very difficult.

A.2.4. Community 4

1. **Community agent**

Tasks

- The community has 4 agents in total
- Their duties include maintaining the system, communicating with the community and making minor repairs. If something major issues comes up, they call the boss, who is in the free city.

Technical characteristics

- The grid has 219 connections.
- New batteries installed in August 2023, total 192 batteries.
- The batteries charge during the day and switch off when fully charged. Then the electricity goes directly to the grid, otherwise it flows in the batteries.
- The lines operate at 240 volts.
- The grid has installed pole lightning protection on almost pole.

Technical knowledge

- The agents clean the transmission lines twice a week, noting a significant performance improvement when they do so.
- They turn the grid off during heavy rainfall and lightning.

Grid performance and reliability

- There is electricity available almost 24 hours a day, operating from 8 a.m. to 6 p.m. from 7 p.m. till noon and again from 2 a.m.to 8 .a.m. The other days there is electricity for about 10 hours a day.

- The micro-grid shuts down between 6 .p.m. and 8 .p.m because of the temperature, the batteries need to cool down. The system shuts down if the State of Charge is 100%, when there is strong wind or heavy rain.
- On Fridays and Thursdays, the load is high due to people cooling items, causing the grid to shut off frequently.

Barriers and Challenges

- Accidents occur, once there was a major fire caused by lightning that set the lines and batteries on fire.
- Wind during the rainy season can break the transmission lines, and poles are sometimes damaged by vehicles or objects.
- People often hang clothes on transmission lines, contributing to transmission line breakdown issues.
- Electricity theft is a problem and those who don't pay for their top-up get disconnected.
- Once there was a huge fire due to lightning, and there was no electricity for one year.
- The freezers are also a problem, when there is a market and the days before the market, they use a lot of electricity, so sometimes the demand is too high.

Improvements

- The community desires more batteries, additional PV panels, and cooling systems to prevent the batteries from overheating and expiring prematurely.
- The agents want faster technical support, as they must call the operator, who then has to find a technician in Freetown to repair the grid, resulting in wait times. If this is improved real grid faillures can be solved faster.

2. **Household 1**

Appliances and usage

- This household uses electricity for light, TV, phone charging, and a DVD player, and consists of five members.
- The light is really convenient and the outside light provides a sense of security

Communication

- Agents listen to most of the issues

Grid performance and reliability

- Over time, the grid's reliability has improved, and the new batteries are working well
- They have 24-hour electricity however power availability decreases during market days and the rainy season
- The family member buys top-up credits and pays a monthly fee but feels that the top-up purchased does not match the electricity received.
- Sometimes their meter stops working, and hitting it seems to restore functionality.

Barriers and challenges

- Blackouts are often due to rain and wind.
- Broken lines are not a common sight.
- She is not allowed to say if there are thieves, since her man is a policeman.
- A major fire once caused by lightning affected the lines and meters, leaving the community without electricity for about a year.
- The family member can not confirm if the solar panels are cleaned regularly as they are too far away.

Improvements

- She would like a more reliable meter that does not require hitting to work.
- When asked what else they would like to see improved about the grid, residents had no idea, with light being considered sufficient.

3. **Household 2**

Appliances and usage

- This household uses three lights, a freezer, TV, DVD player, water heater, and phone chargers, and consists of eight members. The freezer, bought by the husband from an old man who no longer wanted it, is used to store items for sale, and the earnings are used to buy top-up credits for electricity.

Grid performance and reliability

- They state the grid is reliable, except on Thursdays when there are blackouts due to the high demand from the market, as many people use freezers to cool goods.
- Electricity is usually turned off from 5 p.m. to 8 .p.m., and sometimes until 11 .p.m., due to the heat.

Barriers and challenges

- The family member knows why there is no electricity at these hours, that is because of the heat.
- The resident sees not seen broken lines
- The solar panels are clean.
- There is no clear evidence of electricity theft, but the resident acknowledges that it could happen given the general fairness issues in the country.
- A fire once left the community without electricity for a year.
- The family member state that the agents takes their job serious, and clean often. She think once a week.

Relation

- The agents feel responsible, if something is wrong, a family member can come and report the problem. They will fix it . Calling does not help.

Improvements

- The member would like to see improvements in the top-up system, specifically a way to monitor the remaining balance, as there is a belief that the amount paid does not equate to the electricity received. There is a perception of buying more top-up but receiving less light.

A.2.5. Interview summary - Grid operator

This grid operator is in charge of many micro-grids in Sierra Leone. Their future plans are focused on scaling up capacities in the communities, aiming to reach more communities and expanding deployment. But now a day different challenges arise.

The grid operator collaborates with the government and has encountered problems, especially around customer complaints and resolutions and how to resolve technical issues on sites. There are times when the government's positions do not align with theirs. Investments are made in US dollars due to funding from the organisation UNOPS, which means they must deal with inflation. The Electricity and Water Regulatory Commission (EWRC) sets the prices for the electricity for the mini-grids. For any tariff adjustments, Power Leon must go through the authorities of major government agencies in charge of tariff adjustment. The tariffs are to low to for replacements and for maintenance cost and operational costs. However, the response from these authorities is slow. They haven't responded to requests for tariff adjustments in about a year. Also because of the elections the government does not want to increase the tariffs.

Another challenge they face is finding talent with technical capacities close to the community to support these micro-grids. They have tried to up-skill people with a certain foundation or skill set to perform basic technical tasks and support operations. The micro-grids are very remote and there are many of them, making it costly and impractical to send technicians from Freetown to these communities every time an issue arises. To overcome this challenge, it is crucial to have someone with technical capacity nearby to intervene in maintenance from time to time.

Operationally, the weakest components are the batteries, which have a long list of operating conditions that must be met. Lead-carbon batteries are used, as this is the cheapest option. This is chosen by the grid designers. When these conditions are compromised or unmet, the batteries degrade quicker and reach their end of life faster. Batteries are twice as likely to reach the end of their battery lifetime. Normally these batteries can last about 10 years, in the climate of Sierra Leone they do not work for more than 5 years. High temperature is a big problem. Ensuring replacement costs is a significant burden for operators, who would prefer not to replace batteries two or three times within the micro-grid's lifetime. The operator is exploring innovative solutions to address this issue, although the specifics of these solutions are not detailed.

A.2.6. Interview summary UNOPS - Monitoring and Evaluation specialist

UNOPS constructed 93 mini-grids throughout Sierra Leone in rural areas with the Rural Renewable Energy Project (RREP). The project, initiated in 2019, extended the activities of some Ebola response programs from 2016, when Sierra Leone faced a significant Ebola outbreak. During that time, UNOPS specialized in alternative energy-based electricity solutions to support health centers, which suffered from a severe scarcity of electricity. This to provide electricity to facilitate healthcare facilities and help people in areas. For instance, during the Ebola pandemic and even the COVID pandemic, health centers often had to perform surgeries using phone lights due to the lack of electricity. UNOPS targeted 50 rural locations, providing solar-powered electricity with storage capacities to support health service delivery in hospitals. Initially, the system sizes were very small.

After the pandemic, UNOPS aimed to increase the capacity of these systems and provide electricity to the communities using a hub-and-spoke model centered around health facilities. They targeted 94 mini-grids. In 2019, this became one of the largest projects of its kind in Africa.

UNOPS decided to develop the distribution grid and increase the capacity of the systems from 16 kilowatts based on technical studies and demand analysis to understand the specific activities in those areas. Health facilities received free electricity, but the demand in rural communities exceeded estimates. Some households started small shops with refrigerators or bought televisions, increasing evening electricity demand. The systems were often not capable of meeting this demand, necessitating upgrades, such as adding batteries and solar panels. For example, the fishing site near the Lungi airport area required a system upgrade.

The system performance issues are attributed to various factors, including the quality of components and the mismatch between supply and demand. Even with demand assessments, quality assurance processes and criteria. he batteries, with a lifespan of three to five years, often need to be replaced earlier than the 25-year lifespan of mini-grids.

After constructing a micro-grid, UNOPS handed it over to the Ministry of Energy. The Ministry of Energy regulates tariffs. A portion of the tariff collected is reserved in a state-regulated account for future operation and maintenance. However, the specialist mentioned that accessing these funds is a challenge for the system operator. Power Leon, the operator of these mini-grids, faces difficulties in accessing these reserved funds causing delays in maintenance and battery replacements. This leads to low performance of some mini-grids after three to five years.

The specialist from UNOPS emphasized the need for a standard operating process to streamline access to these resources. Regulatory barriers between the Ministry of Energy and the operators created significant bottlenecks. UNOPS suggested that, while they could offer guidance and support the development of standard operating processes, but they are not in a position to take full ownership. In his opinion, the government needs to take the lead in implementation and rest the ultimate responsibility with the government.

Despite UNOPS expertise and experience, responsibility for ongoing operation and maintenance, including access to funds for battery replacement, lies with the government and operators. In his view, the government should prioritise leadership in operational and maintenance activities to ensure uninterrupted electricity supply.

B

Actor Analysis

This chapter contains the actor analysis, which contributes to understanding the dynamic context in which the micro-grid system operates. The actor analysis is based on literature and the semi-structured interviews in the site visits, see Appendix A. Through this analysis, the roles, objectives, and relationships of the actors are mapped out. These insights serve as input for defining Key Performance Indicators (KPIs) and system requirements, and they assist in determining the boundaries within which mitigation strategies must fit.

B.1. Involved actors

Ministry of Energy

The Ministry of Energy is the policy authority and indirectly involved. It is responsible for formulating and implementing policies and regulation of the energy sector in Sierra Leone. It developed a energy sector road maps with an implementation plan of national policies, including rural electrification. In addition, it provides oversight functions across the entire energy supply chain for all sector agencies which include the EGTC, EDSA and EWRC [57]. The overall objective of the Ministry of Energy is to produce and distribute sufficient energy from renewable and clean sources and to improve the access to for the majority of the population while ensuring a stable and affordable energy supply, with a small focus on rural areas to improve electricity supply in rural communities. [6].

Energy and Water Regulatory Commission

The Sierra Leone Electricity and Water Regulatory Commission (EWRC) is a independent regulation authority and regulates the utility service providers in the electricity and water sectors in accordance with government laws, acts and policies. The EWRC is indirectly involved and promote rural electrification and established specific micro-grid regulations. These regulations streamlined requirements for renewable energy projects and aligned energy policies, making the investment climate more attractive for micro-grid initiatives. Besides the regulations the EWRC set end-users tariffs for the electricity [21], [58], [20]. The tariffs for the electricity generated by the micro-grids is based on the financial integrity for operation and maintenance for a grid operator, and ensure affordable electricity for users [59], [40], [39]. Their overall objective is ensuring the reliability of electricity and water supply and to promote consumer interest by creating affordable tariff structures [58].

UNOPS

The United Nations Office of Project Services (UNOPS) is the funding organisation and system designer. It is a non-governmental organisation that provides infrastructure, procurement, and project management services in developing countries to support the achievement of the Sustainable Development Goals. UNOPS invested in 93 micro-grids on specific sites in Sierra Leone in the Rural Renewable Energy Project (RREP) [40]. The objective of UNOPS in terms of this project is to provide reliable, clean and affordable electricity to facilitate healthcare facilities and people in developing counties [40].

Micro-grid operator
The licensed micro-grid operators, primarily utilizing solar micro-grid generation technology, include Winch Energy SL, Off-Grid Power, Power Leone, and Solar Era Holdings SL. These operators are responsible for the design and the construction of generations assets, operation and maintenance, and management of solar micro-grids [39]. Maintaining profitable and to cover at least operation and maintenance cost is the main objective. This to provide affordable, reliable, and scalable electricity to satisfy users from micro-grids to communities in Sierra Leone [60].

Community Agent
The community agent is a local operator. It is a community member assigned to take charge of the micro-grid within the community. They are responsible for the contact between the community and the system operator. In addition the agent is responsible for carrying out minor operational and maintenance tasks to ensure the functioning of the system [38], [39]. The objective for the community agent is to maintain a operational system, as a functioning system enhances job security and guarantees their own access to electricity [38].

The users
The community members, including households, businesses, schools, and community health centres (CHCs), rely on the micro-grid for their electricity needs, seeking affordable and reliable electricity [3]. The availability of electricity has a significant impact on their livelihoods, as it increases their potential to generate income. Evening lighting extends their productive hours, allowing them to conduct activities after dark and enabling businesses to operate longer [7],[38].

B.2. Power-Interest grid

The actors involved and their objectives are placed into a power-interest grid, as illustrated in Figure B.1. This visualisation provides valuable insight into the relative importance of each actor. The actors located in the upper-right quadrant are those that require close management.

The Ministry of Energy holds significant power, as it acts as the policy authority. Without the Ministry's approval, UNOPS cannot implement these projects. However, deployment relies highly on funds from UNOPS, which makes UNOPS powerful. However, the Ministry's focus is largely on the energy sector as a whole, with only a small portion dedicated to rural electrification [6]. In contrast, the EWRC has a greater interest in rural electrification, as it developed the Rural Electrification Strategy [59]. UNOPS also shows interest in these initiatives, though it can invest in other projects aimed at improving the livelihoods of the population. The system operator, community agent, and users all demonstrate high interest. The users demonstrate a high level of political awareness, which extends even to remote areas [39] [40]. However, they face financial constraints due to the underdevelopment of Sierra Leone, particularly in rural regions. The system operator holds some power, as the government relies on them for the realisation of the micro-grids, highlighting the dependencies within the system.

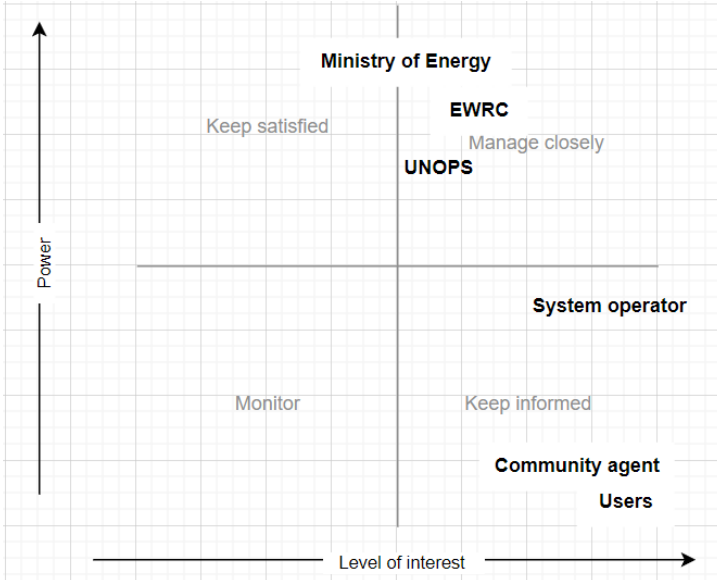


Figure B.1: Power and Interest Grid

B.3. Actor relationships

As the involved actors are clear with their roles and objects the ownership and relations between these actors are defined. An overview of the relationships and dependencies between actors is given in Figure B.2.

- UNOPS implements the micro-grid project on behalf of Sierra Leone's Ministry of Energy to help expand the access to energy in rural areas. It designed and implement distribution assets of the micro-grids. Once the micro-grids are designed and deployed the ownership is handed over to the Ministry of Energy and the system operator.
- The grid operators execute this on behalf of the government. The system operators operate under government authorization, and these entities do not hold a monopoly, as four system operators have been granted licenses by the government to operate micro-grids. The operators collaborate with donors, and investors to implement strategic funding agreements aimed at maintaining and expanding their services in Sierra Leone.
- The micro-grids themselves are on daily operational basis community-based, meaning that it is managed by a community agent. The community agent works under the direction of the operators and reports serious unsolvable issues to the gri operator who can send a mechanic. The agents does not have the resources, engineering knowledge or authority to influence over the system's operations or policies [40], [39].

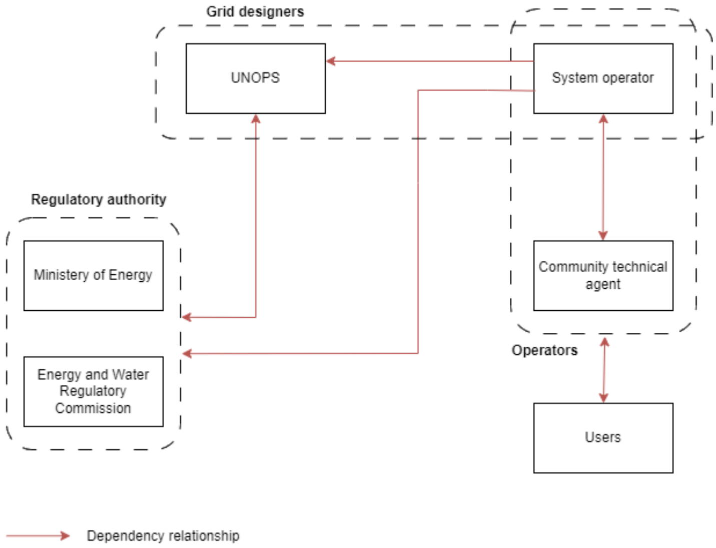


Figure B.2: Outline of organisation and dependencies for operation of the solar micro-grid in Sierra Leone.

B.4. Challenges between actors

The goals and relationships of different actors may involve problems, the challenges between actors are shown below.

The system operator - UNOPS
Once the development phase is completed, UNOPS hands over ownership of the micro-grids to the government and the system operator and is no longer responsible [40]. However, from the perspective of the system operator, UNOPS remains accountable for the distribution of assets in the event of a failure. While the grid operator is responsible for the maintenance and operation of the micro-grids. Grid operators are unable to generate sufficient revenue to cover the replacement costs of these assets. Therefore, UNOPS should assume responsibility for replacement costs in such cases, according to the grid operator [39].

The system operator - Ministery of Energy and EWRC
The government takes over the micro-grids from UNOPS, along with the quality assurances and regulatory responsibilities. UNOPS stated that there is a lack of a standardised operating process, which poses challenges for the execution and maintenance of the micro-grids. The absence of a standardised operating process results in prolonged procurement processes, Accessing financial resources is difficult, thereby delaying the replacement of assets. This consequently results in the underperformance of the micro-grids. The system operator agrees with this assessment, highlighting that the operation and maintenance of the micro-grids are complicated by these issues [39] [40].

Additionally, the EWRC has set the end-user tariffs in consultation with the system operator. This amount was determined during the negotiation process at the beginning of the project. According to an interview with the system operator, significant investments were made in dollars due to the international nature of UNOPS. This has impacted the system operator's revenues as inflation and exchange rates have risen significantly in recent years. The inflation rate has exceeded the system operator's calculated risk threshold, resulting in a lack of financial resources to maintain and operate the micro-grids [39]. New tariff negotiations should take place with the Ministry of Energy and EWRC, to have sufficient resources available for maintenance. However, negotiating with the government is difficult, as the government is complaining about the high tariffs for electricity from micro-grids[39].

It is not uncommon for governmental authorities to adopt particular positions due to the political volatility in certain communities. This becomes particularly evident in rural areas, where the level of political engagement outside the capital is still a daily topic of conversation [38], [60]. The community member finds the electricity tariffs too high [38]. Following recent elections in 2023, the government has focused on gaining public support, making it sensitive to any financial burdens that might affect citizens, including potential increases in micro-grid tariffs. Despite efforts to persuade the government to raise tariffs, this has not been achieved [40].

Users - the system operators
The limited financial resources contribute to performance issues of the micro-grid [39]. Reliability problems reduce user satisfaction and decrease their willingness to pay, which can lead to disconnections [38], [25]. Additionally, the economic conditions place significant pressure on the use of the system. Once users experience the benefits of electricity, it becomes challenging for them to disconnect [38]. The low economic climate may result in tariffs becoming unaffordable for users, exceeding the perceived value of electricity [38]. However, grid operators require some profit to cover operation and maintenance costs [39].

This highlights the challenges between meeting user requirements and maintaining system performance. Users desire low electricity costs, prompting the government to avoid raising tariffs. However, low tariffs result in insufficient funding for proper maintenance, leading to performance issues with the micro-grid. These performance problems, in turn, reduce user satisfaction, creating a difficult cycle to manage. A balance must be found between users and system operators to ensure the continued functioning of the grid within acceptable tariff and performance level.

C
Mitigation costs

The appendix shows the capital and operational costs for two possible mitigation strategies.

C.1. Financial overview batteries and solar panels

Table C.1 show the calculations of solar panels and lead-carbon batteries. In this case, the expansion of the system in kW and the additional costs are considered. Table C.1 shows that the operational costs of batteries are cheaper compared to solar panels, and the capital cost of batteries is also lower.

The capital cost of the solar panel is 1500 USD per kW, with an expected lifetime of 20 years [89]. The annualized cost for the solar panel is 75 USD per kW per year [89].

The battery system has a capital cost of 300 USD for a battery with a discharge rate of 2 kWh over 1 hour [83], [90], [89]. With an expected lifetime of 5 years, the cost is 30 USD per kW per year [38].

	Solar panel	**Lead-carbon battery**
Capital Cost [USD/kW]	1500 [89]	150 [89], [90]
Operating Cost [USD/kW·y]	15 [89]	3 [89]
Lifetime [y]	20 [89]	5 [38]

Table C.1: Costs micro-grid components solar panel and battery

D

Appendix D

In appendix is related to the deployed model in this research. Some validation, input parameters and and sensitivity results are state in this appendix.

D.1. Micro-grid topology validation

In order to validate whether the lengths measured during the fieldwork match the actual length of the micro-grid, the measured lengths are compared with the lengths in Google Maps.

Lengths of all the transmission lines are showed below, Figure D.1. The total length of the transmission line from node 11 to node 22 (yellow arrow) is 400 m on the maps (see Figure D.2) and 396 m according to the site visit data Table D.1. The transmission line from node 14 to node 6 (blue arrow) measures 250 m on the maps and 267 m on the site visit list. This confirms the accuracy of the lengths measured and entered in the model.

Line ID	Bus0	Bus1	Length	Carrie	s_nom	type
PVnode0	PV	node0	**0.005**	AC	53	24-AL1/4-ST1A 0.4
PVbattery	PV	battery	**0.001**	AC	53	24-AL1/4-ST1A 0.4
batterynode0	battery	node0	**0.001**	AC	53	24-AL1/4-ST1A 0.4
node0node24	node0	node24	**0.058**	AC	53	24-AL1/4-ST1A 0.4
node0node1	node0	node1	**0.067**	AC	53	24-AL1/4-ST1A 0.4
node1node2	node1	node2	**0.065**	AC	53	24-AL1/4-ST1A 0.4
node2node3	node2	node3	**0.035**	AC	53	24-AL1/4-ST1A 0.4
node3node4	node3	node4	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node4node5	node4	node5	**0.035**	AC	53	24-AL1/4-ST1A 0.4
node1node15	node1	node15	**0.01**	AC	53	24-AL1/4-ST1A 0.4
node15node9	node15	node9	**0.073**	AC	53	24-AL1/4-ST1A 0.4
node9node8	node9	node8	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node8node7	node8	node7	**0.03**	AC	53	24-AL1/4-ST1A 0.4
node7node6	node7	node6	**0.03**	AC	53	24-AL1/4-ST1A 0.4
node9node10	node9	node10	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node10node11	node10	node11	**0.043**	AC	53	24-AL1/4-ST1A 0.4
node9node12	node9	node12	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node12node13	node12	node13	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node13node14	node13	node14	**0.087**	AC	53	24-AL1/4-ST1A 0.4
node15node16	node15	node16	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node16node18	node16	node18	**0.02**	AC	53	24-AL1/4-ST1A 0.4
node18node19	node18	node19	**0.035**	AC	53	24-AL1/4-ST1A 0.4
node19node21	node19	node21	**0.035**	AC	53	24-AL1/4-ST1A 0.4
node21node22	node21	node22	**0.02**	AC	53	24-AL1/4-ST1A 0.4
node22node23	node22	node23	**0.05**	AC	53	24-AL1/4-ST1A 0.4
node24node25	node24	node25	**0.015**	AC	53	24-AL1/4-ST1A 0.4
node25node26	node25	node26	**0.04**	AC	53	24-AL1/4-ST1A 0.4
node26node27	node26	node27	**0.05**	AC	53	24-AL1/4-ST1A 0.4
node12node29	node12	node29	**0.01**	AC	53	24-AL1/4-ST1A 0.4
node1hospital	node1	hospital	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node2hh2	node2	hh2	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node3hh3	node3	hh3	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node3hh4	node3	hh4	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node3hh5	node3	hh5	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node3hh6	node3	hh6	**0.042**	AC	53	24-AL1/4-ST1A 0.4
node4hh7	node4	hh7	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node4hh8	node4	hh8	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node4hh9	node4	hh9	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node4hh10	node4	hh10	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node5hh11	node5	hh11	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node5hh12	node5	hh12	**0.033**	AC	53	24-AL1/4-ST1A 0.4
node5hh13	node5	hh13	**0.025**	AC	53	24-AL1/4-ST1A 0.4

(a) Transmission line characteristics

Line ID	Bus0	Bus1	Length	Carrie	s_nom	type
node9hh14	node9	hh14	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node8hh15	node8	hh15	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node8hh16	node8	hh16	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node8hh17	node8	hh17	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node8hh18	node8	hh18	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node7hh19	node7	hh19	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node6hh20	node6	hh20	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node6hh21	node6	hh21	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node10hh22	node10	hh22	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node10hh23	node10	hh23	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node10hh24	node10	hh24	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node10hh25	node10	hh25	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node11hh26	node11	hh26	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node11hh27	node11	hh27	**0.05**	AC	53	24-AL1/4-ST1A 0.4
node12hh28	node12	hh28	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node12hh29	node12	hh29	**0.03**	AC	53	24-AL1/4-ST1A 0.4
node29hh30	node29	hh30	**0.01**	AC	53	24-AL1/4-ST1A 0.4
node29hh31	node29	hh31	**0.01**	AC	53	24-AL1/4-ST1A 0.4
node13hh32	node13	hh32	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node13hh33	node13	hh33	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node14hh34	node14	hh34	**0.042**	AC	53	24-AL1/4-ST1A 0.4
node14hh35	node14	hh35	**0.067**	AC	53	24-AL1/4-ST1A 0.4
node16hh38	node16	hh38	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node16hh39	node16	hh39	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node16hh36	node16	hh36	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node16hh37	node16	hh37	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node18hh40	node18	hh40	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node18hh41	node18	hh41	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node19hh42	node19	hh42	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node19hh43	node19	hh43	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node19hh44	node19	hh44	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node21hh45	node21	hh45	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node21hh46	node21	hh46	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node21hh47	node21	hh47	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node22hh48	node22	hh48	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node23hh49	node23	hh49	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node23hh50	node23	hh50	**0.03**	AC	53	24-AL1/4-ST1A 0.4
node24hh51	node24	hh51	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node25hh52	node25	hh52	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node25hh53	node25	hh53	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node26hh54	node26	hh54	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node26hh55	node26	hh55	**0.017**	AC	53	24-AL1/4-ST1A 0.4
node26hh56	node26	hh56	**0.02**	AC	53	24-AL1/4-ST1A 0.4
node27hh57	node27	hh57	**0.033**	AC	53	24-AL1/4-ST1A 0.4
node27hh58	node27	hh58	**0.017**	AC	53	24-AL1/4-ST1A 0.4

(b) Transmission line characteristics

Figure D.1: Transmission line characteristics

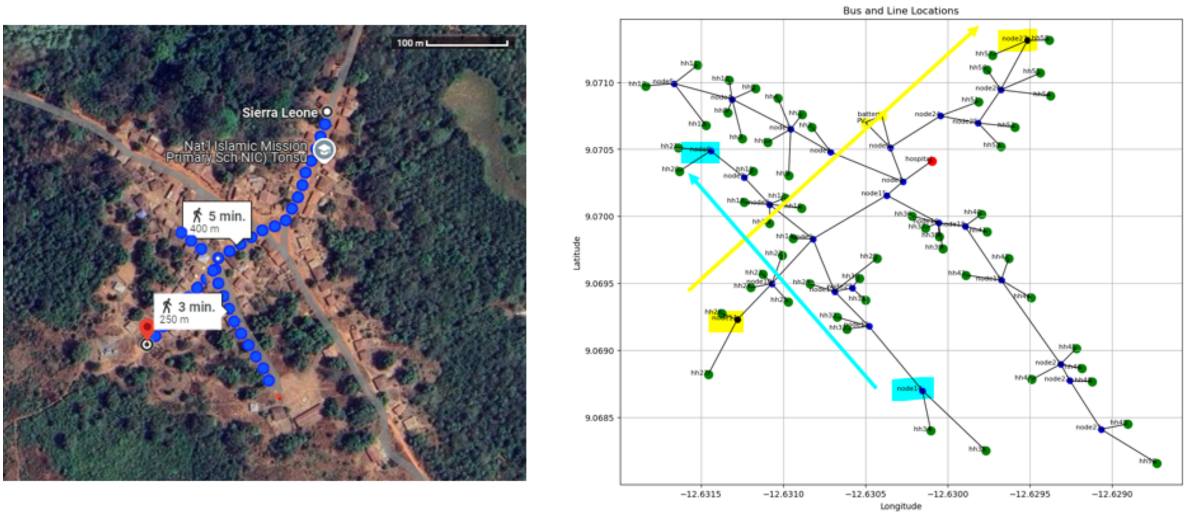


Figure D.2: Length of transmission lines on the map

D.2. Input variables

D.2.1. Transmission lines

For the transmission lines, no detailed information is found. Therefore out of a set of standard lines in PyPSA, the transmission line is chosen. Aluminum conductors are used as they are characterized by their low cost and are commonly employed for high and medium voltage transmission overhead lines [91]. It is assumed that the micro-grids in question have only one voltage level, 220 volts (since 3 ot 4 for has only this voltage level).

For this research, the micro-grid transports power at a single voltage level, with the transmission system consisting of 230 Volt transmission lines. The technical inputs are shown in Table D.1.

Standart Linetype Pandapower [42]	**Voltage (Volt)**	**Reactance x (Ohm per km)**	**Resistance r (Ohm per km)**	**Nominal current (kA)**	**Apparent power (MVA)**
24-AL1/4-ST1A 0.4	230	0.335	1.2012	0.14	53

Table D.1: Transmission line characteristics as input

D.2.2. Battery characteristics

The input variable of the battery in the model are shown below. The lead-carbon batteries are 2kWh each and are interconnected. Information is obtained from literature and technical documents.

Storage Unit [83]	**Nominal power**	**Storage efficiency [92]**	**Dispatch efficiency [92]**	**Standing loss percentage [83]**
Lead-carbon battery	72 kWp	0.93	0.93	$5.55x10^{-05}$

Table D.2: Battery characteristics as input

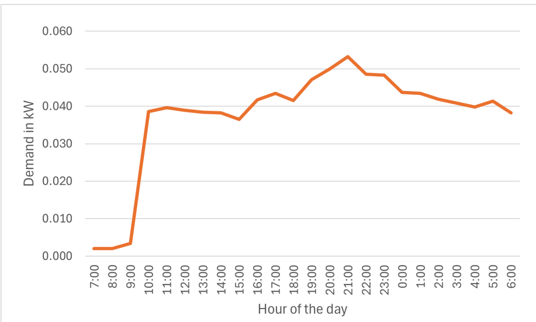
D.2.3. Overview all input parameters

Input parameters		Value	Unit
Number of connections		58	Connections
Transmission lines type		24-AL1/4-ST1A 0.4	
Transmission line standard characteristics:			
	Type	Overhead line	
	Nominal frequency	50	Hz
	Line resistance	1.2012	Ohm per km
	Line reactance	0.335	Ohm per km
	Shunt capacitance	11.25	nF per km
	Nominal current	0.14	kA
	Wire cross-section	24	mm^2
Nominal voltage		220	Volt
Average length of transmission lines		See table ..	
Storage efficiency		93	%
Dispatch efficiency		93	%
Storage standing loss		5.56E-05	kWh
Storage capacity		0.072	kW
PV efficiency		1	%
PV capacity		0.0016	kWp
Generation profile		See table ..	
Load profile		See table ..	
Ambient temperature		45	°C

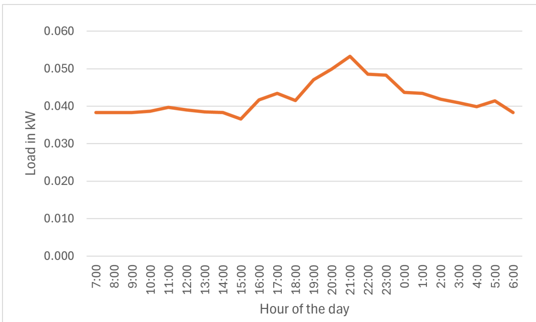
Table D.3: Input parameters for the system

D.3. Input data load profile

Figure D.3 shows the original dataset with outliers and the adjusted load profile dataset after applying forward filling.



(a) The average load profile per connection



(b) The adjusted load profile

Figure D.3: The original and adjusted load profile per connection

D.4. Extrapolation of the capacity fade curve

A fade curve illustrates the expected battery lifetime. Figure Figure D.4 shows the fade curve and the different phases of a lithium-ion battery. According to the study by Johnen et al., the capacity degradation rate follows a sigmoidal curve, consisting of three distinct phases [70]:

- Phase 1: Slow Degradation - The capacity decreases gradually.

- Phase 2: Rapid Degradation - The rate of capacity loss accelerates.

- Phase 3: Slow Degradation - As the capacity reaches a lower threshold, the degradation rate slows down again.

This sigmoidal model allows for the estimation of battery capacity degradation over a number of cycles, using the following formula:

$$f(x;\beta) = \beta_1 - \beta_2 \cdot x - \frac{\beta_3}{1+\exp\left(-\frac{x-\beta_4}{\beta_5}\right)} + \frac{\beta_3}{1+\exp\left(\frac{\beta_4}{\beta_5}\right)} \tag{D.1}$$

The five parameters in the equation modelling the curve, these are explained in Figure D.4.

$\beta 1$ = Nominal capacity $\beta 2$= Linear degradation rate $\beta 3$= Maximum drop in capacity due to rapid degradation $\beta 4$ = Inflection point (cycle number where rapid degradation starts) $\beta 5$= Controls the steepness of transition

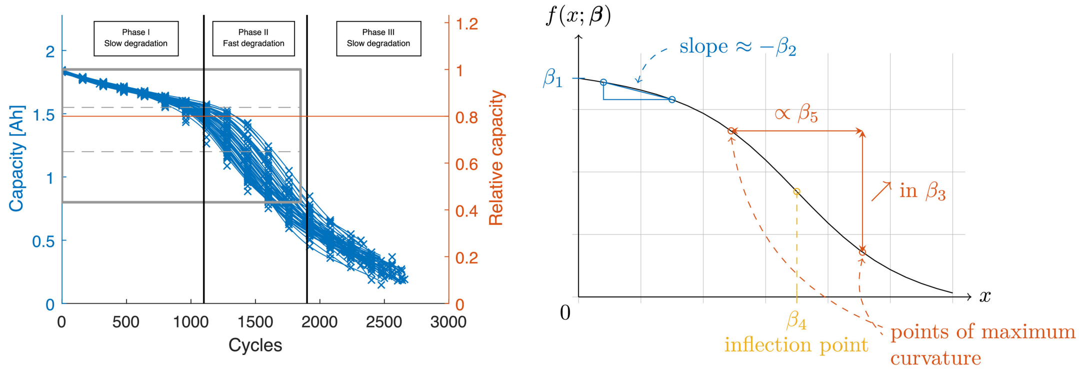


Figure D.4: Capacity fade curve battery including parameters [70]

The fade curve used to determine the battery lifetime in this study is shown in Figure Figure D.5 [68]. The normalised capacity is only plotted up to 50%. Since the entire battery lifecycle is crucial for this study, data extrapolation is performed using curve fitting to estimate values beyond the available data range. A sigmoidal function is fitted to the available data points to predict the missing data.

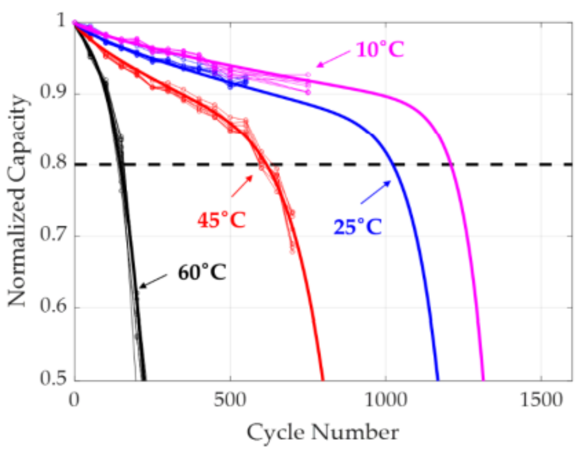


Figure D.5: Capacity fade curve battery under different temperatures [68]

The objective is to accurately determine the parameter values β_1 to β_5 of Figure D.4 so that it closely match the original fade curves, enabling the extension of the curves beyond 50%. Parameters β_1, β_2, β_4, and β_5 can be directly derived from the available data, while β_3, which determines the length of the steep section of the curve, must be estimated. A longer steep section indicates a shorter battery lifespan.

The Python fitting function, which uses non-linear squares, is employed to estimate β_3. This function optimises the fit by iterative adjusting the parameters to best align with the available data points, with β_3 presenting the greatest uncertainty. The resulting parameters are used to generate a sigmoidal curve representing the battery capacity over its entire lifetime, see Figure D.6. See section 9.2 for validation of the estimated curve.

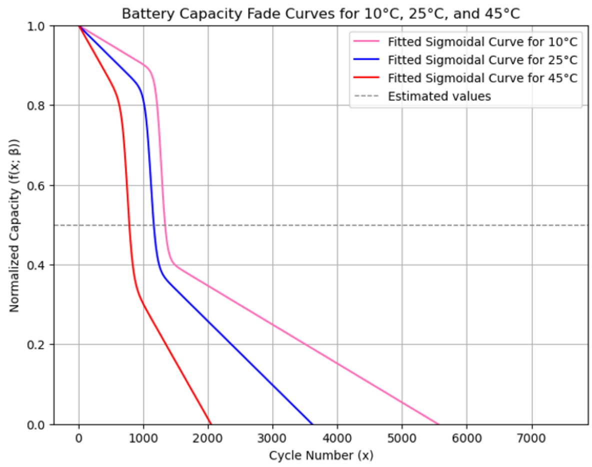


Figure D.6: Extrapolation of capacity fade curve battery under different temperatures

D.5. Sensitivity analysis

D.5.1. Sensitivity outcome expectations

It is expected that the load profile and battery performance will have a more substantial impact on the KPIs than the characteristics of the transmission lines. In the rainy season, where the State of Charge (SoC) of the battery is very low due to limited solar production, see Figure 9.4, a 20% reduction in load would increase the SoC. Small micro-grids can be sensitive to available electricity and demand, meaning that small changes can have an impact. This is equally true for changes in battery parameters. However, a change in transmission line type and length only results in a minor effect, as the reduction in line resistance and reactance is negligible due to the small micro-grid system.

D.5.2. Soc Sensitivity

Figure D.7 illustrates the variation in the State of Charge (SoC) when the transmission line type is changed, demonstrating that while transmission line characteristics do affect the model, they are not sensitive enough to influence the KPIs. The parameter adjustments for transmission lines in the base case and sensitivity analysis are presented in Table D.1

		SoC base case	SoC sensitivity change line	Sensitivity	SoC sensitivity length -20%	Sensitivity
4-Jul	7:00:00	**0**	0	0	0	0
4-Jul	8:00:00	**0.18228**	0.18228	0	0.18228	0
4-Jul	9:00:00	**1.71863**	1.71864	5.81859E-06	1.71863	0
4-Jul	10:00:00	**4.29286**	4.29287	2.32945E-06	4.29286	0
4-Jul	11:00:00	**7.86777**	7.86778	1.27101E-06	7.86777	0
4-Jul	12:00:00	**12.2536**	12.2537	8.16087E-06	12.2536	0
4-Jul	13:00:00	**17.0394**	17.0395	5.86875E-06	17.0394	0
4-Jul	14:00:00	**21.1798**	21.1799	4.72148E-06	21.1798	0
4-Jul	15:00:00	**24.4311**	24.4312	4.09314E-06	24.4311	0
4-Jul	16:00:00	**25.7219**	25.722	3.88774E-06	25.7219	0
4-Jul	17:00:00	**25.1111**	25.1112	3.9823E-06	25.1111	0
4-Jul	18:00:00	**22.8466**	22.8467	4.37702E-06	22.8466	0
4-Jul	19:00:00	**19.9111**	19.9112	5.02232E-06	19.9111	0
4-Jul	20:00:00	**16.7982**	16.7983	5.95302E-06	16.7982	0
4-Jul	21:00:00	**13.4756**	13.4757	7.42082E-06	13.4756	0
4-Jul	22:00:00	**10.4487**	10.4488	9.57057E-06	10.4487	0
4-Jul	23:00:00	**7.43793**	7.43804	1.47891E-05	7.43794	1.34446E-06
5-Jul	0:00:00	**4.71211**	4.71223	2.54663E-05	4.71213	4.24438E-06
5-Jul	1:00:00	**2.00242**	2.00255	6.49214E-05	2.00244	9.98791E-06
5-Jul	2:00:00	**0**	0	0	0	0
5-Jul	3:00:00	**0**	0	0	0	0
5-Jul	4:00:00	**0**	0	0	0	0
5-Jul	5:00:00	**0**	0	0	0	0
5-Jul	6:00:00	**0**	0	0	0	0

Figure D.7: Sensitivity of SoC after changing transmission line type

Input parameters	Value base case	Value sensitivity
Type	Overhead line	Overhead line
Nominal frequency	50 Hz	50 Hz
Line resistance	1.2012 Ohm per km	0.5939 Ohm per km
Line reactance	0.335 Ohm per km	0.3 Ohm per km
Shunt capacitance	11.25 nF per km	12.2 nF per km
Nominal current	0.14 kA	0.21 kA
Wire cross-section	24 mm^2	48 mm^2

Table D.4: Input parameters transmission line sensitivity