Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Power Engineering

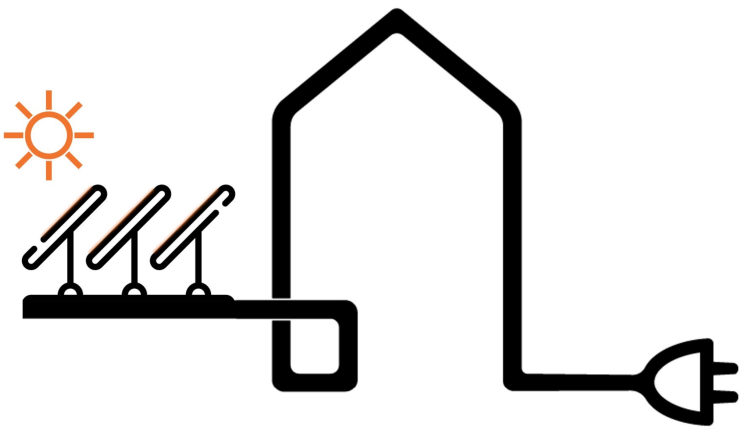
Varshan Erik Shankar

Off-Grid Microgrid Design Considerations for Rural Electrification

A Modeling Tool for GridVille NTNU

Master's thesis in Energy and Environmental Engineering, Electrical Power System
Supervisor: Steve Völler, NTNU
Co-supervisor: Ida Fuchs, NTNU

June 2023



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Abstract

This Master's thesis has made significant strides in advancing rural electrification efforts, mainly focusing on the design and implementation of microgrids. The primary contribution is developing a versatile Python-based tool tailored to the needs of GridVille NTNU, a technical student organization at the Norwegian University of Science and Technology, a project aiming to provide sustainable electricity to off-grid, rural areas.

The tool incorporates a multi-objective optimization approach that considers various variables and constraints, such as energy source selection, energy storage, load profiles, and applying the Multi-Tier Framework for energy access. It has been designed with a user-friendly structure that allows usage at various levels, from basic to advanced, depending on the user's technical expertise. This makes it a valuable resource for a broad user base, from students doing the technical sizing to board members involved in budget planning or similar tasks.

The tool's practicality and reliability were demonstrated through a case study and validated using real-world data. It was found to be accurate and capable of handling a variety of scenarios and conditions, which is critical in the rapidly evolving field of renewable energy and microgrids.

In addition to the tool's development, this thesis provides insights into microgrid design considerations based on field experiences from Kenya and Tanzania. These experiences underscore the importance of understanding the local context and highlight the crucial role of community engagement, the necessity of understanding local energy consumption habits, and user education about energy utilization.

The study also contributes to several Sustainable Development Goals (SDGs) set forth by the United Nations. It directly aids GridVille in achieving these goals by enabling the organization to size and implement off-grid microgrids optimally, thus improving living conditions in underserved communities.

Despite the significant contributions of this study, there are potential areas for improvement and future work. More extensive error handling and data validation steps could enhance the tool's user-friendliness. Furthermore, as the tool evolves and becomes more complex, significant restructuring might be needed to maintain its modularity and navigability.

In summary, this Master's thesis presents a comprehensive study on rural electrification focusing on the design and implementation of microgrids. It provides a practical tool for microgrid sizing, offers insights into design choices, and shares first-hand field experiences. This work can greatly aid GridVille and similar projects in their mission to bring sustainable and reliable electricity to off-grid, rural communities. However, it is an ongoing journey that calls for continuous learning and adaptation to technological advancements and evolving field experiences.

Sammendrag

Denne masteroppgaven har gjort betydelige fremskritt i arbeidet med elektrifisering av rurale områder, spesielt med fokus på design og implementering av mikronett. Hovedbidraget er utviklingen av et allsidig Python-basert verktøy skreddersydd for GridVille NTNU, en teknisk student organisasjon ved Norges teknisk-naturvitenskaplige universitet, med et prosjekt som har som mål å levere bærekraftig elektrisitet til strømløse områder i verden.

Verktøyet inkluderer en multi-objektiv optimaliseringstilnærming som tar hensyn til forskjellige variabler og begrensninger, som valg av energikilde, energilagring, lastprofiler og anvendelsen av rammeverket for energitilgang på flere nivåer. Det har blitt designet med en brukervennlig struktur som tillater bruk på forskjellige nivåer, fra nybegynnende til avansert nå, avhengig av brukerens tekniske kompetanse. Dette gjør det til en verdifull ressurs for en bred brukerbase, fra medlemmer som gjør teknisk analyse til styremedlemmer som er involvert i budsjetteringsplanlegging eller lignende oppgaver.

Verktøyets praktiske nytte og pålitelighet ble demonstrert gjennom en case-studie og validert ved bruk av virkelige data. Det ble funnet å være nøyaktig og i stand til å håndtere en rekke scenarier og forhold, noe som er kritisk i det raskt utviklende feltet for fornybar energi og mikronett.

I tillegg til utviklingen av verktøyet, gir denne oppgaven innsikt i vurderinger rundt design av mikronett basert på feltopplevelser fra Kenya og Tanzania. Disse erfaringene understreket viktigheten av å forstå den lokale konteksten og fremhevet den kritiske rollen til samfunnsengasjement, nødvendigheten av å forstå lokale energiforbruksvaner og behovet for brukeropplæring om energibruk.

Denne masteroppgaven bidrar også til flere av FNs bærekraftsmål. Den hjelper direkte GridVille med å oppnå disse målene ved å muliggjøre optimal dimensjonering og implementering av selvstendige mikronett, noe som forbedrer levekår i uland.

Til tross for de betydelige bidragene fra denne studien, er det potensielle områder for forbedring og fremtidig arbeid. Verktøyets brukervennlighet kan forbedres med mer omfattende feilhåndtering og datavalideringstrinn. Videre kan det, ettersom verktøyet utvikler seg og blir mer komplekst, være nødvendig med betydelig restrukturering for å opprettholde modulariteten og navigerbarheten.

Oppsummert, presenterer denne masteroppgaven en omfattende studie om rural elektrifisering med fokus på design og implementering av mikronett. Den gir et praktisk verktøy for dimensjonering av mikronett, gir innsikt i designvalg og deler feltopplevelser. Dette arbeidet kan i stor grad hjelpe GridVille og lignende prosjekter i deres oppdrag med å bringe bærekraftig og pålitelig elektrisitet til strømløse områder i verden. Det er imidlertid en pågående reise som krever kontinuerlig læring og tilpasning til teknologiske fremskritt og utviklende feltopplevelser.

Preface

This project thesis is written at the Department of Electric Energy (IEL), earlier called the Department of Electric Power Engineering. The thesis is dedicated to GridVille NTNU. I want to thank my supervisor from NTNU, Steve Völler, and my co-supervisor, Ida Fuchs, for valuable guidance. Having supportive and understanding supervisors is crucial in a master's thesis like this. Steve has provided invaluable support and input, demonstrating remarkable flexibility in accommodating adjustments. Ida has contributed significantly by offering coding assistance, helping plan the field trip, and overall being an incredible source of support for both GridVille and this thesis.

Numerous parties have been involved in making this master's project possible. Firstly, I would like to thank Maurice Sudkamp, the founder of GridVille NTNU, as neither this thesis nor GridVille NTNU would exist without him. Furthermore, I express my gratitude to the entire board and all members of GridVille Team 21/22. I also appreciate the entire project management team of GridVille Team 22/23 for their general contributions and support throughout the thesis.

I thank the travel planners and guides who facilitated the trip to Tambatu Island. I would also like to thank Dr. Gideon at the Technical University of Mombasa for hosting and providing incredibly enlightening discussions and conversations. I would also thank Eco Moyo Education Center in Kenya. Special gratitude to my travel companions, Marie Bakken, and Rikke Enger Dihle, for the trip and their overall support and contributions to this master's thesis. Thank the Department of Electric Energy for providing funds for the trip and GridVille NTNU for the financial support they provided.

Interviews and discussions were conducted throughout this thesis. Hence, I would like to thank the members of GridVille who shared their knowledge and thoughts. Additionally, I thank Per-Odd Eggen and Nils Kristian Rossing from The Resource Centre for Mathematics, Science and Technology for their valuable insights and reflections.

Lastly, I would like to express my gratitude to all my family and friends who have supported me throughout the master's journey. Thanks to my classmates from Renewable Energy Engineering'17, EMIL'17, and EMIL'18.

Trondheim, July 2023
Varshan Erik Shankar

Contents

Acronyms

AC Alternating Current. 12, 13, 22, 36

BESS Battery Energy Storage System. xi, 21–24, 27, 38, 39, 60, 66

CAES Compressed Air Energy Storage. 21

CoD Chairman of the Department. 41

CSV Comma Separated Values. 52, 58

DC Direct Current. ix, 12–14, 17, 22, 58

DERs Distributed Energy Resources. 9, 12

DF Diversity Factor. 15, 17

DoD Depth of Discharge. 23, 24

ESMAP The World Bank's Energy Sector Management Assistance Program. 27

HAWT Horizontal-axis Wind Turbines. 20

MES Multi-energy Systems. 15, 16

MTF Multi-tier Framework. ix, 27, 28, 39

NRMSE Normalized Root-Mean-Squared Error. 16, 17

NTNU Norwegian University of Science and Technology. ix, 2, 3, 5, 9, 30–33

P2P Peer-to-peer. 26

PV Photovoltaic. ix–xi, 5, 8, 12–14, 17–20, 38, 42, 43, 45, 51, 54, 55, 58, 59, 64, 65, 70, 73, 75, 77–79, 81

RAMP Remote-Areas Multi-Energy Systems Load Profiles. 16, 17, 56, 57

SDGs Sustainable Development Goals. ix, 3, 4, 72, 73

SE Swarm Electrification. 26, 27

SE4All Sustainable Energy for Al. 27

SHS Solar Home System. ix, 13, 14, 26–28, 45

SoC State of Charge. 23, 24, 76

TUM Technical University of Mombasa. ix, 41, 42

VAWT Vertical-axis Wind Turbines. 20

List of Figures

List of Tables

1 Introduction

1.1 Background

1.1.1 The Impact of Electricity Inaccessibility

Electricity is considered an essential component of modern society and is regarded as one of the most important inventions ever. It powers our homes, provides us with light and heat, and is vital to our daily lives. In Norway, electricity is necessary to function in this modern age, and its importance cannot be overstated. Unfortunately, about 770 million people worldwide still lack access to electricity, particularly in Asia and Africa, as shown in Figure 1. However, upon closer examination of specific countries, it becomes apparent that these nations also have significant disparities. There are several countries depicted in this Figure 1 that may appear to have 100% electricity access, but they still have economically disadvantaged regions lacking adequate electrical infrastructure [1].

> *"The definition used in the international statistics adopts a very low cutoff for what it means to have access to electricity. It is defined as having an electricity source that can provide fundamental lighting and charge a phone or power a radio for 4 hours daily."* [2]

This lack of access to reliable and affordable electricity significantly impacts people's quality of life. Those living in areas without access to electricity may be unable to access essential services such as healthcare, education, and communication, as well as necessary amenities such as refrigeration and cooking [1].

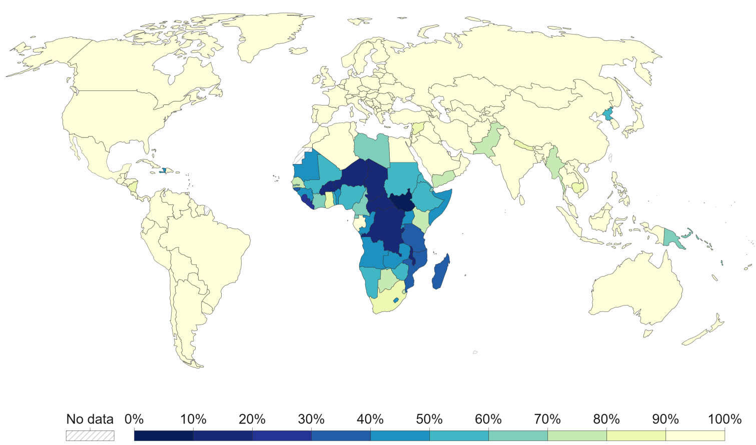

Figure 1: Share of the population with access to electricity [2].

Living without electricity makes people unable to take advantage of modern technology. It requires individuals to rely on alternative energy sources, such as candles, firewood, or oil lamps, for lighting and cooking. Daily tasks can become time-consuming and physically demanding without electrical appliances, from washing clothes by hand to heating water on a stove. Living without electricity can impact communication and information access, as individuals may be cut off from the world's news and events without access to the internet or television. Access to a computer is essential in modern society as individuals without access will lose important job opportunities. Access to electricity for lighting is also considered essential, as there is a lack of safety and security at night. Both the lack of light and computers will also have a significant impact on a child's education.

The lack of access to electricity limits people's daily activities and has broader implications for their overall quality of life. It impacts essential conveniences and restricts access to vital services like healthcare. It can result in food spoiling, which can have negative health effects and increase the difficulty and length of time involved in cooking and food preparation. Also, in locations lacking electricity, individuals may utilize dangerous fuels like kerosene, which can harm health, such as respiratory issues and even death [1], [2].

Furthermore, according to several publications, the COVID-19 disaster undid years of advancement in the electrification of rural areas. According to data from the International Energy Agency, the number of people in Sub-Saharan Africa without access to electricity rose between 2019 and 2021. From 2015 to 2019, it originally declined annually by an average of 9%. An update following the pandemic could potentially exacerbate the already dire nature of the data represented in Figure 1. This trend would most likely be observed in several regions across Asia and other parts of the world with inadequate electrical infrastructure [1].

1.1.2 Technical Organizations Empowering Change

Technical organizations encompass student associations at NTNU focused on technology development. There are eight such organizations, each working towards different goals. These range from organizations like Orbit, dedicated to building satellites for various purposes, to Revolve, which constructs and competes with world-class race cars. A common objective among these technical organizations is to provide students with practical experience and an opportunity to apply the theory they learn by participating in product design, construction, and production. All the technical organizations at NTNU and their logo is represented in Figure 2, and a more detailed list of the organizations is given in Table A.1 in Appendix A [3], [4].

All technical student organizations consist solely of students from different backgrounds and are entirely operated by volunteer students who apply to join the organization. These organizations strive to accomplish as much as possible without relying on professors or sponsors. They have everything from students working on mechanical aspects, conducting advanced strength calculations and material testing, designing and building electrical components, working with HR, financial calculations, and marketing.

Figure 2: A representation of all the technical student organization at NTNU and their logo [5].

However, some students discovered the need for a project fusing technology with humanitarian help. As a result, GridVille was created in collaboration with Engineers Without Border and NTNU Trondheim [6]. GridVille is the first technical student organization in the world to design and build a microgrid with renewable energy sources for rural areas. Each year, a new team of technical student personnel will be hired; the first group was hired in August 2021. Every year, an experience transfer is carried out through documentation and meetings, enabling new teams to build upon the work of the previous one.

Prior to GridVille, there had not been a yearly project of similar nature. GridVille intends to set the groundwork and serve as an example for other universities worldwide to launch such initiatives. The objective is to encourage students to participate in the global effort to increase access to electricity, with the ultimate goal of reducing the worldwide number of people without electricity from 770 million to a lower figure, step by step [5].

GridVille aids in achieving several UN SDGs. By offering electrification, GridVille supports Goal 1: "No Poverty," promoting economic opportunities and living conditions in underserved communities. The organization also aids Goal 4: "Quality Education," enhancing learning via electricity provision in rural areas, enabling extended study hours and use of educational tech tools. Refer to Figure 3 for a representation of the SDGs relative to GridVille's work.

Figure 3: SDGs in relation to GridVille's work [7].

Furthermore, GridVille backs Goal 7: "Affordable and Clean Energy" by creating renewable energy-powered microgrids, countering energy poverty and fossil fuel reliance. This commitment to SDGs signifies GridVille and similar organizations' pivotal role in addressing global challenges and fostering sustainable development [8].

1.2 Motivation

GridVille is a newly established organization, so the technical foundation must be established. In 2021, the first board of GridVille comprised students from other technical student organizations such as Fuel Fighters and Revolve. Fuel Fighters aims to develop the world's most energy-efficient electric car, while Revolve competes in the Formula Student competition to create the fastest racecar [4], [9]. These organizations provided valuable organizational experience to the GridVille board to help start the organization. However, they needed more technical foundation and experience to build a microgrid that needed to be developed. 2021 was also the first year GridVille hired technical members. Figure 4 represent the first GridVille team.

Figure 4: The first team in GridVille [5].

In the decision-making process of a technical organization, there are various factors to consider that go beyond industry-related considerations. While GridVille's primary objective is not to generate profits, it must still consider market prices and product reliability and quality to ensure the sustainability and longevity of its annual projects. Making good economic decisions in the design of the microgrid will also help to maintain the involvement of sponsors and partners in the projects. Oversizing the microgrid poses a risk of allocating excessive funds towards it that could otherwise be utilized for future projects.

Several microgrids have been delivered to various locations by different humanitarian organizations. An example is the Eco Moyo Education Centre, a free primary education center that educates hundreds of children [10]. The electricity at this school is supplied using a microgrid consisting of PV panels and battery storage. Only the peak load was considered when sizing this microgrid, resulting in an oversized microgrid, as the average load is significantly lower than the peak load. The cost of this microgrid could have been significantly reduced by sizing the microgrid based on the entire load profile instead of just the peak load [11]. This is just one example of why an optimization script should be used to determine a microgrid's optimal size, considering various real-life factors such as location, grid purpose, and user restrictions [12].

However, two additional factors will be crucial for GridVille to consider: reliability and safety. These are highly significant considerations as safety concerns both the user of the microgrid and the students working on its design and testing. In the coming years, GridVille anticipates encountering new factors requiring its attention. Therefore, it will become increasingly beneficial to have a customized optimization script for accurately calculating and simulating the optimal size of the microgrid. This approach would be more valuable than relying on an existing system that may not account for all the necessary factors, become outdated, or evolve in a different direction from what GridVille requires.

Through my prior involvement with Revolve, I have gained valuable insights and solutions for similar systems. Rather than relying on existing programs, Revolve has developed custom software for various aspects of the car, including real-time monitoring during races, post-processing of aerodynamic simulations, and other in-house scripts and programs. Although some of these programs may not have been particularly unique initially, they have been continually developed over the past decade to meet Revolve's specific requirements and improve efficiency and accuracy. This approach is highly advantageous in annual student projects with limited time constraints.

GridVille aims to replicate the recipe for success utilized by other technical student organizations and recognize the importance of developing a custom script for the optimal sizing of off-grid microgrids. This script will be refined over the next several years, expanding its capabilities to incorporate new functions and perform additional calculations. This master project serves as the initial foundation for building a successful technical student organization [12], [13].

1.3 Scope of the Thesis

This master thesis aims to identify deficiencies in GridVille, aiming to establish a comprehensive knowledge foundation for technical members at GridVille NTNU regarding the sizing of off-grid microgrids at NTNU. The study will explore factors that need to be considered when determining the appropriate size of microgrids, including understanding energy usage patterns and their impact on microgrid design decisions. Furthermore, the research will address specific requirements relevant to GridVille. At the same time, the goal is to create a modeling tool that will benefit GridVille for several years in the most optimal way. The modeling tool developed in this master's thesis will be further enhanced by the technical members of GridVille, becoming increasingly flexible, feature-rich, and sophisticated with each passing year. This tool will serve as a crucial instrument for GridVille to deliver a new grid to a different location every year. This master's thesis goes beyond the development of a tool; it aims to address energy usage in rural regions and establish a foundation for designing in accordance with these requirements.

Key objectives of master thesis:

- Microgrid Sizing for Rural Areas
- Utilization of Energy
- Validation and testing of tool

1.4 Master Thesis Outline

This master's thesis deviates from the conventional format typically followed by traditional thesis assignments. It encompasses multiple aspects related to microgrid sizing, as it involves the development of a tool specifically tailored for student use with a unique approach.To ensure clarity and coherence, an outline is provided to demonstrate the interconnectedness and purpose of each chapter.

Section 1: Introduction

This section aims to lay the groundwork for comprehension by providing pertinent background information and defining the motivations and scope of the master thesis under consideration.

Section 2: Theoretical Concepts of Off-Grid Microgrids for Rural Electrification

The purpose of this section is to introduce the theoretical concepts of off-grid microgrids and provide the relevant equations that will be necessary for the development of the modeling tool. The aim is to provide a foundation of knowledge on how to size an off-grid microgrid for rural areas.

Section 3: GridVille

The purpose of this section is to provide comprehensive information about GridVille and its operations. Understanding GridVille's objectives, vision, current and future plans, as well as any restraints or limitations that may impact their performance, is crucial in comprehending why certain decisions have been made in both the script and the design of the microgrid. This knowledge will allow for informed choices and enable alignment of the optimization script and microgrid design with the needs and goals of GridVille.

Section 4: Microgrid Design Choices for GridVille

This section focuses on discussing various design choices made for GridVille's microgrid. It explores the considerations and factors taken into account when selecting the type of microgrid, energy source, energy storage, and other system components. The section aims to provide insights into the rationale behind these design choices and their implications for the overall performance and effectiveness of the microgrid.

Section 5: Field Trip To Africa

This section provides an account of the field trip to Africa, specifically Kenya and Tanzania. It describes the experiences and observations made during the trip, highlighting the complexities and unique challenges of implementing off-grid solutions in rural settings. The section emphasizes the importance of understanding the local context, community engagement, and user education in ensuring the sustainability and effective operation of microgrids.

Section 6: Existing Programs and Custom Scripts

This section presents an overview of existing microgrid optimization tools, evaluating their capabilities, strengths, and limitations. It highlights the need for a custom tool tailored to GridVille's unique needs, addressing gaps in the existing tools. The section focuses on the development of a user-friendly guide and script, ensuring accessibility and usability for users with varying technical expertise. It also explores the coding architecture, algorithms, and software engineering practices used to implement custom tools, providing insights for future enhancements and modifications.

Section 7 : Creating a Tool for GridVille

This section describes the methodology used to build the custom tool. It outlines the steps taken to ensure the tool's accessibility, usability, and comprehensibility for users with varying levels of technical expertise. The section describes the design principles, user interface considerations, and instructional materials that accompany the tool to facilitate its effective utilization by GridVille's technical members.

Section 8: Results and Validation

This section presents the results of the simulations conducted using the microgrid sizing tool. It showcases the outcomes of different scenarios, including load profiles, PV production profiles, and system performance under various configurations. The section also discusses the validation process, comparing the tool's output with existing codes or empirical data to demonstrate its accuracy and reliability.

Section 9: Discussion

In this section, the findings from the simulations and validation are analyzed and discussed in detail. It examines the implications of the results, identifies strengths and limitations of the tool, and provides insights into the applicability of the tool in real-world scenarios. The section also explores potential areas for improvement and future research.

Section 10: Conclusion

The final section of the thesis serves as a conclusion, summarizing the key findings, contributions, and implications of the research. It reflects on the achievements of the study, provides insights into the relevance and applicability of the developed tool, and identifies avenues for future research and improvements. The conclusion wraps up the thesis by emphasizing the importance of the work in advancing rural electrification efforts and addressing the global challenge of electricity inaccessibility.

2 Theoretical Concepts of Off-Grid Microgrids for Rural Electrification

This chapter introduces relevant theory for the design and sizing of an off-grid microgrid. Theory about microgrids, load profile, solar energy, the use of other energy sources, energy storage, and the prospect of rural electrification is provided. This chapter is based on the specialization project written in course TET4510 at NTNU Trondheim. Section 2.3, 2.4.1, and section 2.6 is taken almost directly from the specialization project.

2.1 Microgrids

Microgrids are a collective of interconnected loads and Distributed Energy Resources (DERs), delineated by specified electrical boundaries, and constitute a regional electrical power system at distribution voltage levels. This system functions as a unified controllable entity and can operate in either grid-connected or island mode. A microgrid operating in island mode implies that the installed generation capacity must exceed the maximum critical load [14].

Figure 5 represents an example of the key elements of a microgrid. Critical loads refer to essential electrical loads or electricity consumers, that must be supplied with power at all times, even during outages. This could include systems like life-support equipment in hospitals, data centers, or any other system where an interruption in electrical supply could have serious consequences. Controllable loads are electrical loads whose power consumption can be adjusted in response to supply conditions, price signals, or grid stability requirements. This adjustment can be achieved through demand response strategies, which could involve reducing or shifting their energy use during peak periods [15], [16].

Fast switching typically refers to the ability of the microgrid to disconnect from and reconnect to the main utility grid quickly. This capability is crucial for maintaining the power supply to the microgrid during utility grid disturbances or outages. Fast switching is often facilitated by a device known as a static switch, which can make this transition in a matter of milliseconds, preventing power interruptions. The utility grid, also known as the main grid or macrogrid, is the larger electricity network to which the microgrid is connected. This grid is typically managed by a utility company and supplies power over a wide area. In the context of microgrids, generation refers to electricity production within the microgrid system. This can be achieved through a variety of sources. Storage refers to systems that store electrical energy for use at a later time [15], [16].

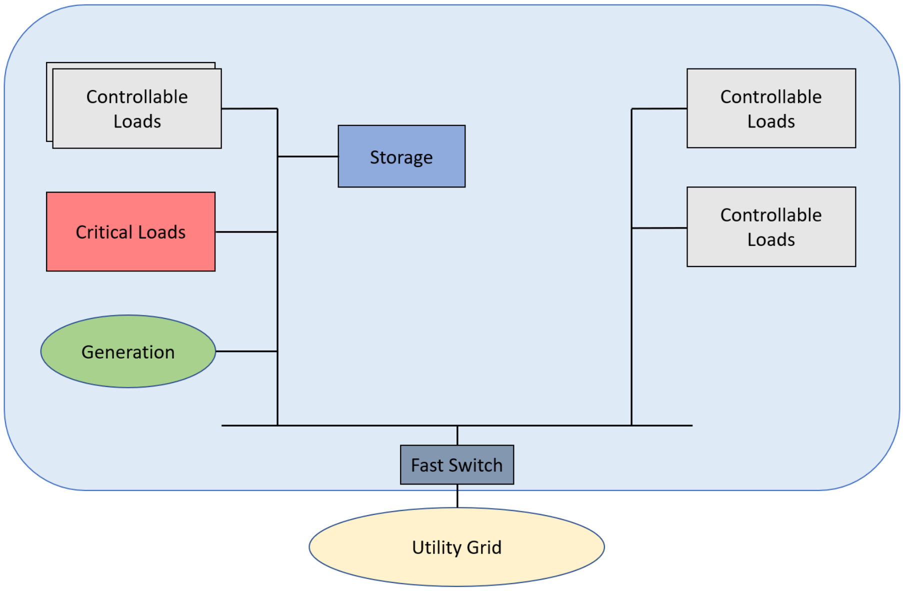

Figure 5: Microgrids represented with electrical boundaries.[15]

The term ”microgrid” is commonly perceived as a novel technology; however, the first DC microgrid was implemented by Edison in 1882. Over the subsequent four years, his company successfully installed 50 DC microgrids. Nevertheless, the advent of the transformer in 1883 facilitated the paradigm shift toward large-scale, centralized AC-based generation, ultimately leading to the decline of Edison's low-voltage, DC microgrid concept. Nonetheless, we are witnessing a global surge in microgrid installations, serving many purposes.

Microgrids offer improved electrical supply quality, grid contingency management, and optimization of localized energy supply. Furthermore, advancements in power electronics have rendered one's reliance on AC and traditional transformers no longer obligatory. Microgrids also play a vital role in the transition toward sustainable practices, as they are increasingly integrated with renewable energy sources such as solar panels on commercial and residential buildings, facilitating the supply of green and renewable energy. Another critical application of microgrids lies in rural electrification efforts, addressing the energy needs of remote areas[14], [15].

One advantage of a microgrid is its capacity to offer a dependable source of electricity in the event of a power loss. Traditional electricity grids are susceptible to failure from mishaps, severe weather, or other occurrences. In contrast, microgrids are designed to operate connected to and synchronously with the traditional centralized grid but also in” island mode,” meaning they can continue providing power to their connected loads even if disconnected from the larger grid [17].

In the event of a power unit failure within a standalone microgrid, such as a hydropower unit, a wind turbine, or both, the system remains operational due to an energy storage system. This functionality is ensured as long as the storage unit can supply power to the connected loads. This becomes particularly crucial in emergency scenarios or regions where the main grid is unreliable[15], [17].

Microgrids are used in both rural and urban areas, effectively increasing energy access, improving energy efficiency, and reducing costs. Microgrids can offer energy access to rural areas with insufficient or unstable power supplies. By minimizing electricity losses from transmission and distribution, microgrids can also help to increase energy efficiency. Additionally, microgrids might offer a cheaper and more reliable source of electricity [18].

Microgrids are also a good solution for rural areas without any prior electricity. It is sometimes far too expensive for the government to expand the national electricity grid to cover some areas due to inadequate infrastructure or other reasons. In other places, citizens are not permitted to join the national electricity grid because of disputes over religion, ethnicity, or other political issues. The usage of microgrids to provide electricity can be especially important in these areas [18].

Microgrids can be either DC microgrids, AC microgrids, or Hybrid. An example of a hybrid microgrid is given in Figure 6 [13].

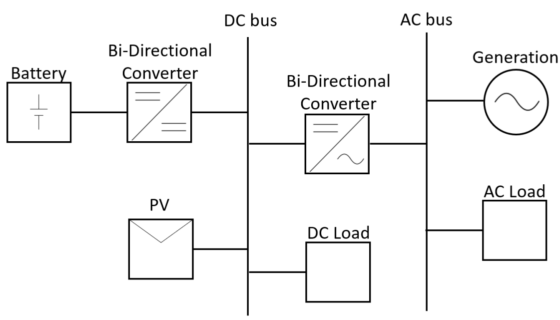

Figure 6: An example of a hybrid microgrid [19].

Hybrid microgrids can operate in different modes, depending on the availability and variability of energy resources. By employing a hybrid microgrid, the advantage arises of seamlessly utilizing both DC and AC appliances without necessitating converters in between. Consequently, the losses associated with such conversions are eliminated, optimizing overall system efficiency [19].

2.1.1 DC Microgrid

DC microgrids are electrical systems that operate using DC. A representation of a typical microgrid is represented in Figure 7. It is usually connected with DC-based DERs such as PV panels. This method improves the efficiency of the energy transfer and use. DC microgrids can eliminate the losses associated with Alternating Current (AC) -DC - AC conversion, which is necessary for conventional power grids because they employ a single voltage level. However, AC or DC energy can be produced in DC microgrids. In a DC system, the system's protection will also be simplified because all components will run at the same voltage [19].

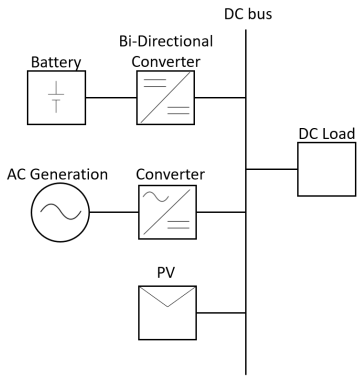

Figure 7: An example of a DC microgrid [19].

The main advantage of DC microgrids is their unidirectional flow direction, which makes it easy to control the power flow by modifying the system's inverter. Power control needs to be concerned with the current flow because power flow depends on the voltage and current direction. Power converters with units connected to the DC microgrid typically have a more efficient architecture. A DC microgrid's adaptability, which may be adjusted to match the unique requirements of a specific site, is another advantage. Another benefit is that many batteries used to store energy are DC, which reduces loss when using renewable energy sources that produce DC. Each conversion from DC to AC or vice versa results in energy loss. Avoiding these losses improves the system's efficiency by maximizing power use for electrical devices. As systems that generate DC power increase and the availability of off-grid DC-based appliances and devices increase, the prevalence of DC based systems increases [13], [19].

The lack of DC equipment and appliances in rural locations is a drawback of employing DC microgrids. Most equipment and appliances in some rural locations are made to run on AC power, making finding DC versions of these products challenging or expensive. The provision of dependable electrical service may become more difficult as a result. The expense of installing and keeping the system is another possible drawback of employing DC microgrid in rural locations. As opposed to their AC equivalents, DC microgrids frequently need specialist hardware and infrastructure, such as DCDC converters and DC distribution lines. In addition, the price of replacing or repairing equipment could go up due to the limited supply of DC products [13], [19].

2.1.2 AC Microgrid

Similar to typical power grids, AC microgrids are built to run on alternating current. A representation of typical AC microgrid is represented in Figure 8. The AC's interoperability with the existing electrical grid is one of their main advantages [19].

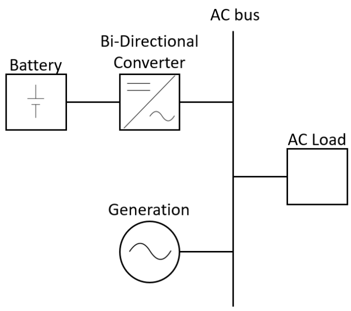

Figure 8: An example of AC microgrid [19].

The same voltage and frequency as conventional power grids are used by AC microgrids, making it simple to incorporate them into the larger grid and share resources like transformers and transmission lines. In these scenarios, an AC microgrid will offer numerous applications with a cost-effective solution [13], [19].

The utilization of AC microgrids offer the advantage of delivering high efficiency when directly supplying AC loads. However, in a case when an AC system uses a DC power generator, the efficiency will be reduced since converters, like inverters, are required to connect to an AC microgrid [13], [19].

2.2 Solar Home System

SHS represent the Level 1 smallest system you can have as a microgrid. These standalone PV systems offer a cost-effective mode of supplying amenity power for lighting and appliances to remote off-grid households. In rural areas that are not connected to the grid, SHS can be used to meet a household's energy demand, fulfilling basic electric needs. Globally, SHS provides power to hundreds of thousands of households in remote locations where electrification by the grid is not feasible [20].

SHS typically operate at a rated voltage of 12 V DC and provide power for low-power DC appliances such as lights and radios. They use appliances such as cables, switches, mounts, structural parts, and power conditioners/inverters. SHS are best used with efficient appliances to limit the size of the array.Figure 9 shows an example of a little SHS system used for lighting [20].

Figure 9: An example of a small SHS at Eco Moyo Education Center in Kenya [21].

A typical SHS includes one or more PV modules consisting of solar cells, a charge controller, and at least one battery. The charge controller and the battery can be located in the device, shown as a yellow box in Figure 9. SHS contributes to improving living standards by reducing indoor air pollution (as they replace kerosene lamps), providing lighting for home study, and enabling work at night. Typical systems costs in the Eastern Africa region range between US$ 170 for a 12 Wp system and up to US$ 2,000 for a 150 Wp system. For developed countries, the average cost per installed watt for a residential-sized system is about US$ 6.50 to US$ 7.50, including panels, inverters, mounts, and electrical items [20].

2.3 Load Profiles

Load profiles refer to the electricity consumption pattern for a particular user, location, or system. They are used to predict and understand the electricity demand and are important in planning and designing a microgrid. Production is usually much larger than consumption when connected to a larger national grid. However, when a smaller grid is operated in island mode, the electricity consumption needs to be calculated precisely. Therefore, having an accurate load profile is of utmost importance to ensure that the microgrid is neither over- nor under-dimensioned [22].

Load profiles can vary depending on the characteristics of both the user and the location. E.g. because of the climate, the type of equipment and appliances that are used, and the time of the day they are used. For example, the load profile for a house will show higher demand during the morning and evening and lower demand when the residents are at work during the daytime [22].

The accuracy of the load profile will directly influence the accuracy of the microgrid size. Undetailed or incorrect load profiles could lead to wrongly sized microgrids. Load profiles are particularly important in rural areas as there will be no other energy sources or microgrids nearby to connect to if the already existing microgrid can not meet the electricity demand [22].

There are several different ways to collect a load profile in rural areas:

- Measured data: The process entails gathering data from electricity meters or other measuring devices to accurately measure the real-time demand of the system over a specified period.
- Simulation: The process involves employing computer models to simulate the system's demand, considering assumptions regarding the load and other relevant factors.
- Load Survey: This process entails gathering data on the specific type and size of electrical appliances and equipment within the system and their usage patterns.

2.3.1 Diversity Factor

Diversity Factor (DF) is a measure of the ratio between the peak load power, $P_{L,peak}$, and the total rated power, $P_{L,total}$. It is typically used in calculating a load profile to represent the extent to which the system's demand is correlated with the total demand of the grid. DF can be calculated using Equation 1 [23].

$$DF = \frac{P_{L,peak}}{P_{L,total}} \tag{1}$$

DF may be more important in rural areas where the mix of end-use loads is more diverse and complex. This is because a higher coincidence factor indicates a higher degree of variations in the demand, which may require larger or more flexible resources to meet the demand. A lower coincidence factor may be sufficient in rural areas where the demand is more consistent or predictable [23].

2.3.2 Methodology of the RAMP Model

As renewable energy sources increase, so does the adoption of Multi-energy Systems (MES) for planning off-grid systems in remote areas. Lombardi et al. developed a model for generating multi-energy loads in rural areas to address this need. This open-source bottom-up stochastic model is adaptable for customization to specific systems and can accurately reproduce both the average daily profile and day-to-day fluctuation in load profiles [24].

Unlike previous models for MES load profiles, which were based on interview data, Lombardi et al.'s model accounts for the inclusion of appliances in the community and allows for the consideration of future devices through stochastic approaches. Implemented in a Python environment, the model is freely available as the Remote-Areas Multi-Energy Systems Load Profiles (RAMP) [24].

Modeling residential load profiles often involves using stochastic approaches to account for random customer behavior. However, these models are typically designed for on-grid systems in industrialized countries where data is more detailed and readily available. In rural areas, such data is often scarce or inaccurate, and off-grid systems require models customized for energy planning rather than forecasting [24].

Mandelli, Merlo, and Colombo developed a bottom-up stochastic approach that incorporates interview-based data and accounts for uncertainties using randomly varying parameters. However, this model does not allow for the inclusion of non-electric loads, such as cooking and water heating. In response, Lombardi et al. propose using an open-source bottom-up stochastic model called RAMP to generate load profiles in remote areas. This model builds upon the approach of Mandelli, Merlo, and Colombo but increases the degree of stochasticity to allow for the modeling of appliances' duty cycles throughout the day [24].

Lombardi et al. compared modeled load profiles to empirical data from a hybrid microgrid system in El Espino, Bolivia, to validate the RAMP model. The system, which includes photovoltaic panels, a battery bank, an inverter, and a diesel generator, was installed in September 2015. In November 2016, Lombardi et al. collected interview-based data and used the RAMP model to generate load profiles [24].

A set of indicators was defined to evaluate the accuracy of the RAMP profiles. The Normalized Root-Mean-Squared Error (NRMSE) is a metric used to evaluate the accuracy of a model in reproducing the shape of an average daily load profile. The equation is represented in Equation 2 [24].

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - y_{pred_i})^2}{\sum_{i=1}^{n} y_i^2}} \tag{2}$$

y_i is the measured value and y_{pred_i} is the predicted value. The NRMSE is calculated by taking the root-mean-squared error of the differences between the measured and predicted values, normalized by the sum of the squares of the measured values [24].

The NRMSE can be used to assess the performance of a model in reproducing the shape of an average daily load profile and can provide insight into the model's accuracy. A lower NRMSE value indicates a better fit of the model to the data. The DF was also used to validate the model and is shown in Equation 1 in section 2.3.1. The resulting error percentage was below 2% for all selected indicators [24].

An exciting outcome with RAMP is how the use of three main layers in the algorithm (*User type*, *User*, and *Appliances*) allows for the creation of unique load profiles for each *User type*, consisting of individual *Users* with independent *Appliances* with different behaviors [24]. The modeling layers are depicted in Figure 10.

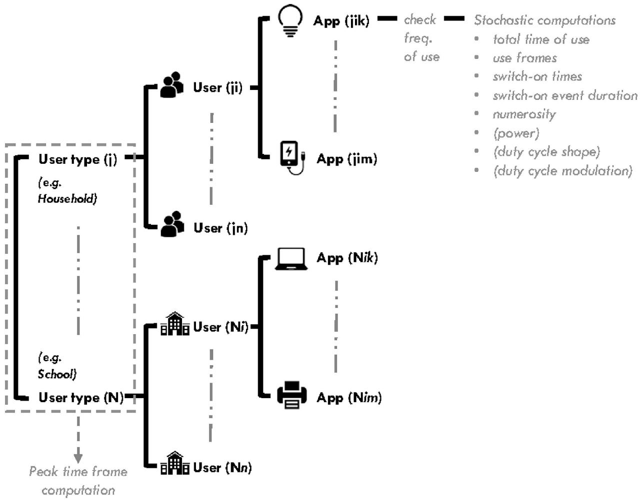

Figure 10: Graphical sketch of the modeling layers. [24, p.435]

The complete load profile generated will vary with each model run due to the stochastic nature of the behavior of the *Users*, and the profiles are generated on a daily basis. This represents the unpredictable nature of the load in the system [24].

2.4 Photovoltaic Panels

PV panels, also known as solar cells, can convert sunlight into electrical energy by generating DC. They consist of a semiconductor material, typically silicon, sandwiched between two conductive layers, and when sunlight hits the semiconductor material, it dislodges electrons, creating an electric current. Multiple PV panels can be combined to form a PV system and can be interconnected in series or parallel configurations. Series connections increase the voltage output while maintaining a constant current, while parallel connections increase the total output current while keeping the voltage constant [25].

Considering the ideal tilt angle and azimuth is important to optimize the annual energy production of PV panels. The tilt angle refers to the panel's inclination relative to the horizontal plane, while the azimuth represents its orientation relative to the south. As a general guideline, the tilt angle should equal the site's latitude but not less than 10 degrees to prevent debris accumulation. The panels should also face the equator, corresponding to an azimuth of 180 degrees in the southern hemisphere. Figure 11 provides an illustrative representation of the tilt angle and azimuth of a PV panel, depicting a fixed tilt angle facing south [26], [27].

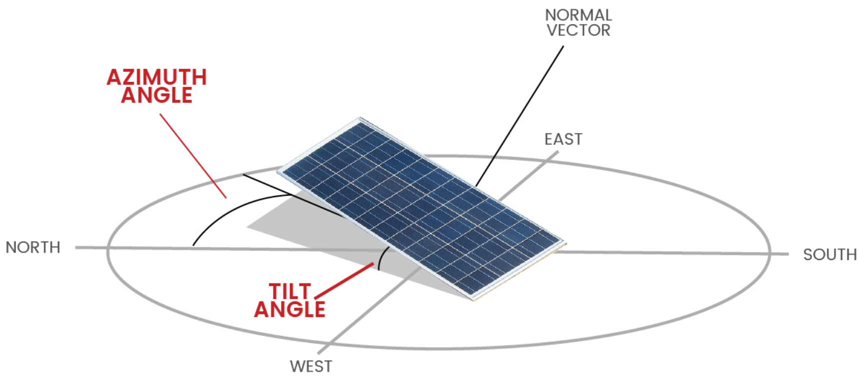

Figure 11: Illustration of PV panel tilt angle and azimuth [26]

PV panels offer a renewable source of electricity that operates without producing greenhouse gases or other pollutants. They are noise-free and require minimal maintenance. However, their efficiency in converting sunlight into electricity is highest when the sun is directly overhead, decreasing with increasing incident angle or shading. PV panels can be cost-effective, particularly in rural areas with abundant sunlight and limited electricity access [25].

2.4.1 Modeling PV

One key aspect of optimizing the design and sizing of PV systems is determining the most appropriate type and configuration of PV modules and inverters for the specific site and application. This can involve trade-offs between cost, efficiency, and durability. Several equations are used in the design and sizing of PV systems. The first three are the current-voltage (I-V) characteristic equation, the power-voltage (P-V) characteristic equation, and the PV module power-current (P-I) characteristic equation [28].

The first one represents the relationship between current and voltage. In contrast, the second one represents the relationship between the power and current of a PV module under a specific set of conditions. Both are often used to predict the electrical output of a PV system. Lastly, the third one described the relationship between the power and current that can be drawn from the PV system. The current-voltage (I-V) characteristic equation is represented in Equation 3 [29].

$$I = I_{SC} - I_0 \left(e^{\frac{V + I \cdot R_S}{n V_T}} - 1 \right) \tag{3}$$

Where:

- I is the current flowing through the PV system (in Amperes)
- I_{SC} is the short-circuit current of the PV system (in Amperes)
- I_0 is current generated in the absence of light in the PV system (in Amperes)
- n is the ideality factor of the PV system
- V is the voltage across the PV system (in Volts)
- V_T is the thermal voltage of the PV system (in Volts)
- R_S is the series resistance of the PV system (in Ohms)

The power-voltage (P-V) characteristic equation is represented in Equation 4.

$$P = V \cdot I \tag{4}$$

Where P is the power output of the PV module (in watts), V is the voltage at the terminals of the PV module (in volts), and I is the current flowing through the PV module (in amps) [28]. The power-current (P-I) characteristic equation is represented in Equation 5.

$$P = V_{oc} \cdot I_{sc} - I \cdot R_s - V \cdot I_0 \tag{5}$$

Where:

- P is the power output of the PV module (in watts)
- V_{oc} is the open-circuit voltage of the PV module (in volts)
- I is the current flowing through the PV module (in amperes)

The fourth equation is the short-circuit current (I_{sc}) equation, which is the maximum current that can be drawn from the array under short-circuit conditions [30]. The equation is represented in Equation 6.

$$I_{sc} = I_0 \left(e^{\frac{V}{nV_T}} - 1 \right) \tag{6}$$

The fifth equation is the open-circuit voltage (Voc) equation, which is the maximum voltage the array can produce under open-circuit conditions. The equation is represented in Equation 7.

$$V_{oc} = nVt \cdot ln(\frac{I_L}{I_0}) \tag{7}$$

Where Vt is the thermal voltage of the cells, which is approximately equal to $k * T/q$, where k is Boltzmann's constant, T is the cell temperature in Kelvin, q is the electronic charge, and I_L is the light-generated current of the cells [31].

The sixth equation is the maximum power point (Pmax), the point at which the array produces the most power. This equation is represented in Equation 8.

$$P_{max} = V_{oc} \cdot I_{sc} \cdot \left(1 - \frac{I_{ph}}{I_{sc}} \right) \tag{8}$$

where I_{ph} is the photocurrent of the PV module. Some other relevant equations should be considered when modeling a PV system. These equations are given and explained in Appendix B [32].

2.5 Other Energy Sources

Wind power and hydropower are two critical forms of renewable energy that harness natural resources to generate electricity. Wind power involves converting wind's kinetic energy into electricity using wind turbines. These turbines capture the wind's energy and convert it into rotational energy, which is then transformed into electricity through an electrical generator. Wind power is renewable and relatively inexpensive, making it a viable option for sustainable energy production.

There are two main types of wind turbines: Horizontal-axis Wind Turbines (HAWT) and Vertical-axis Wind Turbines (VAWT). HAWTs, known as three-bladed wind turbines, are the most commonly used type. They consist of a tower with a rotor at the top and three blades attached to the rotor. VAWTs, on the other hand, have a vertical axis and can take on a variety of shapes, including cylindrical and conical.

Despite their benefits, wind turbines do have some disadvantages. They have a limited lifespan, typically 20-25 years, and can be noisy and visually obstructive. However, they have the potential to provide a reliable source of electricity in rural areas, particularly in regions with solid and consistent winds. They can be sited in various locations, including on-shore, near-shore, and off-shore.

Hydropower involves the generation of electricity using the energy of falling water. This renewable energy source has been used for centuries to power mills and other machinery and, more recently, to generate electricity. Several types of hydropower plants include impoundment, run-of-river, and pumped storage.

Hydropower is renewable, as water is a naturally occurring resource that can be replenished through the water cycle. Hydropower plants also have a relatively long lifespan, with some operating for over 100 years. However, they require suitable topography, with access to a river or other water source with a sufficient drop in elevation. They can also have environmental impacts, such as changes to river ecosystems and the displacement of communities.

Hydropower could be a valuable source for the microgrid when there is a water source nearby a rural area. Small-scale hydro systems are typically less expensive to install and operate, and local communities can easily maintain them.

2.6 Energy Storage

Energy storage is one of the most crucial components of microgrids. It allows excess energy to be stored and used when demand or production is high. Various energy storage options are available today for microgrids, including capacitors, rechargeable chemical batteries, pumped hydroelectric storage, flywheels, and Compressed Air Energy Storage (CAES). Each option has its merits based on various application-specific factors [13], [33].

In Africa and Asia, microgrid development using rechargeable batteries is gaining momentum. The abundance of renewable energy resources, such as solar and wind, combined with unreliable grid infrastructure, makes batteries ideal for microgrid energy storage. The decreasing costs of batteries and their suitability for off-grid and decentralized energy solutions align with the energy access goals in both regions.

2.6.1 Battery Energy Storage System

BESS are a common choice for energy storage in microgrids. They provide a flexible storage option that flattens out the irregularities from intermittent renewable sources. The flexibility, compact size, cost, and versatility of BESS make it a good choice. BESS comprise a combination of components, including batteries, charge controllers, inverters, and software control systems. These components work harmoniously to achieve efficient energy storage, management, and utilization. The integrated nature of these components ensures the proper functioning of a BESS, enabling the effective integration of renewable energy sources, load management, grid support, and overall energy system optimization [34].

Charge controllers are essential components of a BESS that regulate the charging and discharging of the battery. They ensure the proper flow of electrical energy to and from the battery, preventing overcharging or over-discharging, which can degrade battery performance and lifespan. Charge controllers employ various algorithms and control strategies to optimize the charging process and ensure efficient energy management. Inverters are responsible for converting the DC stored in the battery into AC for utilization in electrical systems. They facilitate the integration of the BESS with the grid or other AC-based loads. Inverters also enable the transfer of excess energy from the battery back to the grid or other interconnected systems when necessary [34], [35].

Software and control systems play a crucial role in operating and managing a BESS. They enable real-time energy storage system monitoring, control, and optimization. These systems utilize advanced algorithms and control strategies to ensure efficient energy utilization, optimal battery performance, and seamless integration with the overall energy system. They enable load forecasting, energy dispatch, and grid interaction management. Several types of batteries are available for BESS, including lead-acid, lithium-ion, and nickel-metal hybrid batteries [34], [35].

Each of these types of batteries has its unique characteristics and benefits. Lead acid batteries are commonly used in microgrids. It is relatively cheap and has a long lifespan. However, they can be heavy and have a lower energy density than other battery types. Lithium-ion batteries are a newer type of battery that has gained popularity for energy storage in microgrids due to their higher energy density and lighter weight. Lithium-ion batteries also have a relatively high self-discharge rate, meaning they can lose a significant amount of their charge when not used [33], [34].

Nickel-metal hybrid batteries are another type that is sometimes used for energy storage in microgrids as they have higher energy density and lower self-discharge rate than lead-acid. However, both nickel-metal and lithium-ion have a higher cost. All these types can go into "thermal runaway" in which the cell rapidly heats, leading to fire or dangerous fumes. However, the likelihood and consequences of an event are higher for lithium-ion [13], [33].

2.6.2 Capacity

The capacity of a lead-acid battery is typically measured in amp-hours (Ah). The capacity can be calculated based on the expected daily load and the desired autonomy (the number of days the system should be able to operate without recharging) as shown in Equation 9 [36].

$$Actual\ capacity\ [Ah] = Daily\ load\ [Ah] \cdot Autonomy\ [days] \tag{9}$$

In rural areas, it may be necessary to incorporate additional backup capacity or to design the microgrid to be more resilient to outages [13].

2.6.3 Peukert's Equation

Peukert's equation is used to estimate the actual capacity of a lead-acid battery based on the rate at which it is discharged and is shown in Equation 10. It is important to consider the actual capacity of the battery when designing and sizing a microgrid, as the capacity of a battery will decrease as the rate of discharge increases [37].

$$C = (I_d)^n \cdot T^d \tag{10}$$

n is the battery constant (for lead-acid batteries), I_d represents discharge current in amperes, C is the theoretical capacity of the battery in ampere-hours, and T_d is the discharge time in hours [37].

This equation is not directly related to fire safety. However, it can be an important consideration when designing and sizing a microgrid that utilizes lead-acid batteries for energy storage, as it allows for a more accurate calculation of the required capacity of the battery bank. The primary fire hazard with lead-acid batteries occurs during over-charging when hydrogen gas is produced, which will be less likely when there is a limitation in the maximum output power of the battery [13], [33], [37].

2.6.4 Charge and discharge

The charge and discharge equations can be used to calculate the current required to charge or discharge the battery at a given rate. The charge equation is represented in Equation 11, and the discharge equation is shown in Equation 12 [38].

$$Charge\ current\ [A] = \frac{Capacity\ [Ah]}{Charge\ time\ [hours]} \tag{11}$$

$$Discharge\ current\ [A] = \frac{Capacity\ [Ah]}{Discharge\ time\ [hours]} \tag{12}$$

The State of Charge (SoC) of a BESS refers to the amount of charge stored in the battery, expressed as a percentage of the total capacity. The Depth of Discharge (DoD) of a BESS refers to the amount of capacity that has been used, also expressed as a percentage of the total capacity. The relation between SoC and DoD is represented in Equation 13 [38].

$$DoD = 1 - SoC \tag{13}$$

SoC and DoD are essential considerations when designing and sizing a microgrid that utilizes BESS, as they can impact the performance and lifespan of the battery. In general, it is recommended to operate BESS within a specific range of SoC and DoD in order to maximize their performance and lifespan [13], [38].

2.6.5 Battery Design Considerations

Table 1 shows variables included in deciding what battery type to select for a given system [33].

Table 1: Design Considerations when choosing battery type for a given system. [33, p.3]

Design Considerations	Description
Initial cost	Upfront cost required to purchase the battery system.
Lifetime	Expected operational lifespan of the battery is usually measured in years or cycles.
Engineering costs	Associated with designing and developing the battery system, including costs for research and development, testing, and system optimization.
Maintenance costs	Associated with keeping the battery system operational, including costs for routine inspections, repairs, and component replacements.
Installation cost	Associated with installing the battery system, including costs for labor, equipment, and any necessary modifications to the installation site.
BOP cost	Associated with the supporting and auxiliary components of a battery system, such as the control system, power conditions system, and safety system.
Disposal cost	Associated with safely disposing of or recycling a battery system at the end of its operational life.
The shipping cost	Associated with transporting the battery system from the manufacturer to the installation site.
Environmental impact	Potential effects of the battery system on the environment, including emissions during operation, resource consumption, and waste generation.
Reliability	Ability of the battery system to perform consistently and without failure over its expected operational life.
Safety	Inherent safety features and risks of the battery system, including risks of fire, explosion, and harmful emissions.

2.7 Prospect of Rural Electrification

The prospect of rural electrification holds immense significance in pursuing sustainable development and improving the lives of people living in rural areas. Sizing a microgrid means determining the appropriate capacity and resources to meet the expected demand. In rural areas, this can be particularly difficult.

According to projections by the International Energy Agency (IEA), approximately 70% of individuals currently lacking access to electricity will obtain it through microgrids. The electrification of rural regions in developing countries is already underway in many countries. This is done through the implementation of various small-scale microgrids. Notably, as mentioned in section 2.2, SHS systems are widely utilized by households in rural parts of Africa and Asia.

2.7.1 Swarm Electrification

Swarm Electrification (SE) is an emerging concept gaining considerable attention as an exciting tool to provide last-mile electrification at the lowest possible cost. A swarm grid is similar to a micro-grid, but rather than being a planned network; it is assembled in an ad-hoc fashion, simply connecting available equipment via a controller and expanding the grid as more resources become available [39].

This approach allows the owners of, e.g., SHS to sell excess energy and enables others to gain an electrical connection without investing in their system. This creates an income for the prosumer and helps others to get on the electrification ladder [39].

The concept of SE is based on the principle of Peer-to-peer (P2P) energy trading within an ad-hoc grid. In the context of swarm electrification, an "ad-hoc" grid refers to a power grid that is not planned or designed in advance but grows organically as more resources become available. This could involve adding more solar panels, batteries, or other energy sources to the grid as they become available, and connecting them to meet the community's current needs, rather than following a pre-determined plan or design. This flexibility allows the grid to adapt to changing circumstances and needs, particularly in remote or underserved areas where resources and infrastructure may be limited [39].

The main topics within the literature on Swarm Electrification are identified as optimization, stability, and reliability of these grids to scale up these grids to support small industrial devices. These are the key challenges noted in the current state of the technology. Figure 12 illustrates how the swarm grid evolves [39].

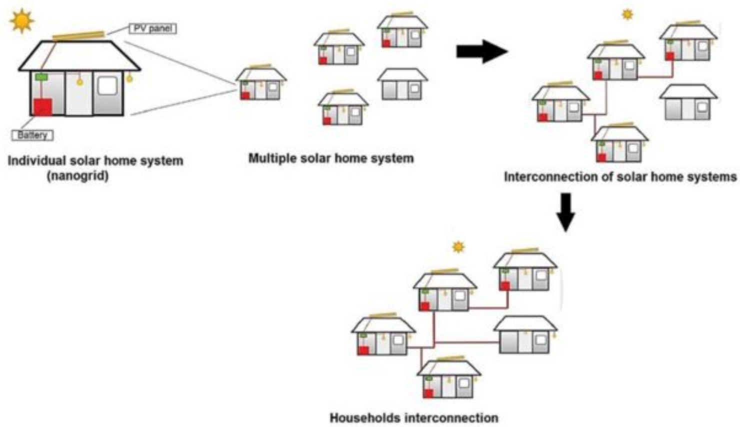

Figure 12: Illustration of the evolution swarm grid.[39]

As depicted in Figure 12, swarm electrification begins with individual homes equipped with, e.g., standalone SHS. Over time, these SHSs become interconnected, facilitated by installing controllers in each home and connecting cables, enabling power sharing. As the network expands, the homes collectively form a grid, and any homes equipped with BESS become integral to the swarm electrification system, contributing to its overall functionality [39].

SE is particularly relevant for rural areas where traditional grid-based electrification may not be feasible or cost-effective. When working on a project related to developing a microgrid for a rural area, consider incorporating some of the principles of SE, such as decentralization and self-sufficiency, in the design and planning [13], [39].

2.7.2 Multi-Tier Framework for Energy Access

MTF is a comprehensive and nuanced approach to defining and measuring energy access. Developed by the The World Bank's Energy Sector Management Assistance Program (ESMAP) and Sustainable Energy for Al (SE4All) initiative, the MTF moves beyond the binary 'have' or 'have-not' approach to energy access. Instead, it recognizes energy access as a continuum of services across five tiers, ranging from Tier 0 (no access to modern energy services) to Tier 5 (providing reliable, affordable, safe energy services around the clock) [40], [41].

The MTF is designed to measure energy access in a way that captures the quality of the service provided, including its adequacy, availability, reliability, affordability, safety, and impact on a user's health. This approach allows for a more accurate representation of the actual energy utility provided to households, productive engagements, and community facilities [40], [41].

In the household locale, the MTF examines access to electricity, access to energy for cooking solutions, and access to energy for space-heating solutions as three separate sub-locales. Each component is assessed based on various attributes, such as capacity, duration, reliability, quality, affordability, legality, and health and safety. The MTF recognizes that improvement in energy access is not a single-step transition but a continuum of increasing levels of energy attributes [40].

The MTF examines the energy supply vis-à-vis critical energy applications for productive engagements. It acknowledges the complexity of measuring energy needs for productive uses due to the diversity of productive enterprises and energy applications. Therefore, it proposes an approach based on surveys of individuals for their key productive engagements and energy needs [40].

In the community facilities locale, the MTF considers five sub-locales—health facilities, schools, street lighting, government buildings, and public buildings. Access to energy for each sub-locale is determined based on surveys of either the facility's users or the facility's providers. An example of how MTF is used is shown in Figure 13 [40].

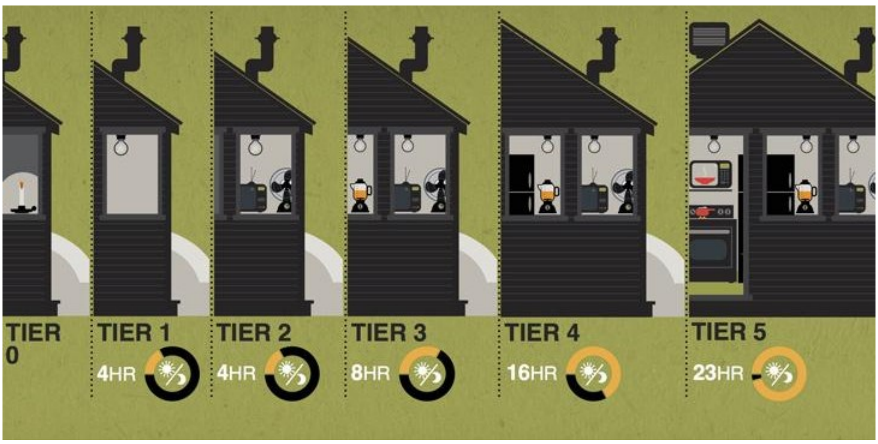

Figure 13: Example of MTF [41].

The MTF also recognizes the significant utility off-grid sources can provide. It includes solar lanterns and other off-grid products in its assessment of energy access. For example, a household using a SHS would be counted as being 'connected' despite the fact that a critical set of basic energy needs were being met. MTF can also be used to determine the appropriate size and capacity of the system based on the specific energy needs and usage patterns of the community it serves. By assessing the quality of the service provided, including its adequacy, availability, reliability, affordability, safety, and impact on a user's health, the MTF can help to identify the level of energy access that the microgrid needs to provide [40], [41].

For instance, a microgrid designed to provide Tier 1 access would need at least

1,000 lumen-hours per day and sufficient energy to keep a well-used mobile phone operational. On the other hand, a microgrid designed to provide Tier 2 access would need to provide sufficient general lighting for a household and power a television and/or fan [41].

2.8 Sizing of Off-Grid Microgrids

Sizing of off-grid microgrids is a critical aspect of their design and implementation. It involves determining the optimal capacity of the microgrid's components, such as photovoltaic panels, energy storage systems, and other energy sources, to meet the energy demand of the community it serves. The goal of sizing is to ensure that the microgrid can reliably supply electricity to meet the load demand while minimizing costs and maximizing the use of renewable energy sources.

The sizing process begins with thoroughly understanding the load profile, representing the community's energy demand over a certain period. This includes both the average and peak demand and the temporal variations in demand. The load profile is a crucial input to the sizing process, as it determines the energy the microgrid needs to supply.

Once the load profile is known, the next step is to size the photovoltaic panels. The capacity of the panels needs to be sufficient to generate enough electricity to meet the load demand, considering the solar irradiance at the location and the panels' efficiency. The sizing of the panels also needs to consider the seasonal variations in solar irradiance to ensure that the panels can generate enough electricity even during periods of low solar irradiance.

The energy storage system, typically batteries, is then sized to store the excess electricity generated by the panels during periods of high solar irradiance and to supply electricity during periods of low or no solar irradiance, such as at night or during cloudy days. The capacity of the batteries needs to be sufficient to meet the load demand during these periods and to provide a buffer for periods of high demand or low generation. The sizing of the batteries also needs to consider their depth of discharge and cycle life to ensure they can reliably store and supply electricity over their lifetime.

Other energy sources, such as diesel generators or wind turbines, may also be included in the microgrid to provide additional capacity and increase the reliability of the electricity supply. The sizing of these sources depends on their availability, cost, and the load demand they need to meet.

The sizing process also needs to consider the balance between supply and demand to ensure that the microgrid can reliably supply electricity without overloading its components. This involves sizing the components to meet the peak demand while also considering the average demand to optimize the utilization of the components and minimize costs. [42], [43]

3 GridVille

This chapter provides an overview of GridVille, including its goals and vision, and outlines a five cycle plan to establish a solid technical foundation. The information presented results from collaborative efforts between the board members of 2021-2022 and the current board members of the team 2022-2023. As the former Chief Electrical Engineer, I made technical and organizational decisions based on my expertise and experience with technical organizations. Additional details about my background and experience can be found in Appendix C. The information in this chapter is based on GridVille's internal meeting notes and documentation, as well as the specialization project written in course TET4510 at NTNU Trondheim. section 3.4 is taken directly from the specialization project.
GridVille is an interdisciplinary project that is distinctive, led by students from NTNU Trondheim, who design and build a sustainable, environmentally-friendly power system for areas with limited access to electricity. The project's primary goal is to develop technology that people can use in their everyday lives, with a strong emphasis on safety, sustainability, and user-friendliness. As an initiative under the auspices of Engineers Without Borders Norway, GridVille is committed to complying with the organization's ethical guidelines.

At NTNU Trondheim, there is a strong focus on technical projects and non-profit organizations involved in humanitarian work, but no project or position combines these two. In August 2020, a group of four students started to explore the feasibility of starting such a project, and it rapidly became evident that there was immense interest among students, departments, and faculties at NTNU. Consequently, the team grew to 15 members to establish the project. In 2021, GridVille began as a project for the first time and employed other students to work on the project's technical and humanitarian aspects.

GridVille has a two-fold vision. Firstly, it aims to provide practical experience to future NTNU students, particularly those pursuing energy and environmental technology studies. Secondly, it aspires to make a meaningful contribution towards the electrification of rural areas, thereby positively impacting the lives of those who lack access to electricity.

As mentioned in section 1.1.2, GridVille's core value is aligned with the United Nations' Sustainable Development goal number 7, which is to "ensure access to affordable, reliable, sustainable, and modern energy for all." [5] In pursuit of this goal, GridVille addresses the following three issues:

- 770 million people lack direct access to electricity
- In developing countries, only 17% of energy consumption is supplied by renewable energy resources
- While financial support for establishing renewable energy in developing countries is increasing, only 12% of this aid goes to the countries most in need.

GridVille's ultimate objective is to provide electricity to individuals residing in small villages, community centers, or small farms in developing countries. GridVille's microgrids will provide electricity within the range of tier 2 and 3. This range of electricity supply is primarily aimed at providing basic amenities and supporting small-scale economic activities. It will enable the users to power their homes, charge their mobile phones, and run small appliances such as radios, fans, and TVs. This electricity supply will not only improve the quality of life for the users but also provide opportunities for small-scale entrepreneurship, such as setting up small businesses like food stalls or phone charging stations. [5]

3.1 Recruitment

GridVille recruits students from NTNU Trondheim exclusively. The organization recognizes the importance of working physically on a project like this, so it limits its recruitment to students from NTNU Trondheim. Typically, the board is hired towards the end of the fall semester, while the remaining members are hired during the autumn semester. By recruiting the board members early, they have sufficient time to prepare for their roles, familiarize themselves with the systems and the organization, and create a project plan for the upcoming year.

All recruitment efforts in GridVille are handled by the marketing and finance team, which includes students only. Recruitment is mainly carried out through stands at NTNU, social media promotions, and posters. As a result, GridVille is made up of a diverse group of students with varying backgrounds, academic disciplines, and levels of prior knowledge. This means that all systems that are developed and all design notes need to consider that there could be students with up to no prior knowledge that will learn about this system before they start to develop it further.

3.2 Long-term Goal and Project Cycle

GridVille aims to establish an annual project that involves designing and constructing a new grid in a different location each year to provide direct access to electricity for individuals who currently lack it. This unique project has not been undertaken anywhere in the world, and GridVille aspires to set a precedent and encourage other universities to initiate similar projects.

Given that ordinary people will utilize the microgrid technology, safety is GridVille's top priority in designing and producing the microgrid. The project's long-term goal is for students to design and build all essential components, allowing them to apply the theories and principles they have learned in their studies to design and construct, thus gaining valuable experience in interdisciplinary project work and international collaboration.

These skills will be valuable to students as they begin their careers. While the components that students will build may not necessarily be technologically advanced, GridVille believes that this project can serve as the foundation for innovative ideas in renewable energy sources, smartgrid and microgrid technology, and technological assistance - all areas where innovative solutions are required to achieve the UN's sustainability goals and Norway's climate objectives.

By providing students with the opportunity to work on a project that contributes to these areas, GridVille aims to cultivate future leaders and innovators in sustainable energy.

3.3 The First Year of GridVille

The organizational structure of GridVille during the first year with members, which was in 2021/2022, is given in Figure 14. It was divided into five main groups: Mechanical engineering, Electrical engineering, Humanitarian Aid and Sustainability, Marketing, and Education.

Figure 14: Graphical representation of the organizational structure

Project management was responsible for coordinating the various groups, monitoring project progress, and communicating with partners. Notably, the organizational structure did not include HR roles. What sets this project apart from other technical projects at NTNU are the Aid & Sustainability and Education groups. These groups ensured the project's sustainability by considering the grid user, determining their needs, analyzing their socioeconomic conditions, and providing instructions for operating and maintaining the grid independently. Combining groups with technological and humanitarian focuses makes this a unique and interdisciplinary project.

In 2021, the team began designing the microgrid, originally intending to use solar and wind as energy sources. However, the project's complexity made it challenging to start with this level of complexity, so a mechanical team was created to focus on the design and production of wind turbines. Additionally, there were many members in the electrical team, leading to a tendency towards chaos instead of positive results during the organization's establishment phase.

GridVille also established cooperation between the University of Kathmandu and NTNU, creating a branch in Kathmandu called GridVille KU. GridVille KU is designing and delivering a microgrid to a nearby community center. Although their approach only partially aligns with GridVille at NTNU's guidelines and perspectives on student learning, their primary objective is to deliver a functional microgrid, purchasing most of the components. While they do not have plans for an annual project, their experience is still valuable and will transfer experience to members of GridVille at NTNU.

This year, GridVille focused on testing various aspects, understanding project complexity, securing partners, and developing a robust plan for the project's future.

3.4 Building a Foundation

Building a microgrid typically involves several steps, including planning and design, procurement and installation of equipment, and commissioning and testing. The exact process and timeline for building a microgrid will depend on the specific requirements and constraints of the project, such as the size and location of the microgrid, the type of energy sources and loads it will serve, and the regulations and policies governing its operation.

GridVille started without any prior organizational knowledge. Building this takes time and cannot be done within a year. A strong knowledge foundation within a technical student organization is crucial for its success and sustainability. This includes not only knowledge about the specific technical field the organization is focused on but also general knowledge about how to run and manage a successful organization. Building this knowledge base can take time, as it requires not only learning and training but also practical experience and experimentation.

However, the effort put into building this foundation will pay off in the long run, allowing the organization to effectively pursue its goals and adapt to new challenges and opportunities. Additionally, having a solid knowledge foundation can also help attract and retain members, as it demonstrates the organization's commitment to excellence and professionalism. In order to ensure GridVille gets the best foundation possible, the board of team 2021 created a five-step cycle.

Cycle 1: Proof of concept

For the first cycle, the goal is to design and implement a control system for a microgrid. This cycle will provide GridVille with the required steps for designing and implementing a microgrid and will lay the foundation for upcoming cycles. The goal is to obtain a stable system.

The first cycle is divided into two steps. The first consists of designing and implementing the microgrid, and the second consists of testing the system in a laboratory. Testing in the lab will be a crucial step for upcoming cycles, and knowledge attained in this cycle will therefore be valuable for the upcoming cycles.

Cycle 1 is completed when GridVille has obtained a stable system. This can be verified through a system test in the laboratory. A successful system test will be obtained when exposed to all realistic operating scenarios without failures.

Cycle 2: Prototype

The second cycle builds upon the first by constructing a microgrid that can withstand outdoor conditions. This will be done through the steps of the first cycle with necessary adjustments for outdoor conditions. The system will be tested in the laboratory and, upon successful testing, tested outside. This cycle aims to determine the necessary adjustments to make the system operate correctly outside.

Cycle 2 is completed when GridVille has a stable system that can withstand realistic operating scenarios without failure.

Cycle 3: Installation of a microgrid in Norway

The third cycle involves using the knowledge gained in the previous cycles to design, implement, and build a microgrid for a specific location in Norway. All steps from the previous cycles will be followed, and the goal is to gain knowledge about designing a grid for a specific location, including protection, system variations, and reliability.

Cycle 3 is completed when GridVille has installed and tested a working system on a given location.

Cycle 4: Implementation in rural area

The fourth cycle aims to design a microgrid for a specific location in a developing country. Knowledge from all previous cycles will be necessary, as well as an understanding of the country's laws and regulations. This cycle aims to learn about the required steps for implementing a microgrid in rural areas.

Cycle 4 is completed when GridVille has built a system that complies with the given requirements for this given location.

Cycle 5: Installation in rural area

The final cycle involves designing, implementing, and installing a microgrid for a specific location in a developing country. Knowledge from all previous cycles will be necessary to achieve this goal.

Cycle 5 is completed when a working system with the requirements has been installed in the given location.

These cycles do not have predetermined timelines. They may take one year or more to complete. The duration is due to the importance of thoroughly completing each cycle to gain a comprehensive understanding of the process, both technically and organizationally. After this, the goal is to design and produce a microgrid each or every second year.

4 Microgrid Design Choices for GridVille

Upon assuming the role of Chief Electrical Engineer at GridVille in 2021, predetermined parameters and a preliminary size for the microgrid had already been selected to commence the project. However, these initial parameters and restrictions were mainly provisional and were established to initiate the organization's operations. Most previous decisions were made hastily and lacked sufficient technical justification.

Making the right design decisions before starting a project like this is important. This includes considering the essential restrictions and factors that must be considered before the technical work can begin. The purpose of this is to make sure that the layout of GridVille is feasible and effective in the initial years of operation. In this chapter, the design choices made in GridVille will be examined in the theoretical framework.

4.1 Type of Microgrid for Rural Areas

In GridVille's goal of providing off-grid solutions for rural areas, an AC microgrid can serve as an ideal solution, primarily when operating in island mode.

When functioning in this standalone capacity, the AC microgrid can ensure a consistent power supply unaffected by disruptions or issues with the main grid.

Most appliances in rural locations are designed to run on AC power, making an AC microgrid a logical choice. By employing an AC microgrid, rural communities can continue to use their existing appliances without requiring costly and complex adaptations or conversions. This direct compatibility reduces the need for extra equipment, keeping initial and operational costs low.

As mentioned in section 2.1, AC microgrids in island mode also offer the advantage of high efficiency when directly supplying AC loads. Since AC is the standard form of power for most electrical devices, the energy produced by an AC microgrid can be directly used, minimizing energy losses from conversions. This increased efficiency is essential in off-grid contexts where every bit of generated power counts.

The more established technology and infrastructure of AC power systems benefit from a larger pool of knowledge and resources. This advantage is beneficial for maintaining and troubleshooting the system, ensuring reliable operation even in the most remote areas.

In a completely off-grid system, it is essential to ensure reliable power generation. This is achievable by including renewable energy sources, such as solar or wind, and energy storage systems in the AC microgrid. The adaptability of AC microgrids to incorporate these sources further strengthens their suitability for off-grid, island mode operation. [13]

4.2 Collection of Data for Load Profiles

Creating detailed load profiles is crucial for GridVille's operations, as inaccuracies could lead to severe economic and technical issues in the sizing of the microgrid. Load profiles are designed using several methods, some of which are mentioned in section 2.3. While measuring actual demand would be optimal, this is not feasible for regions that have never been electrified. Similarly, simulating the load profile could be an alternative, but it demands extensive knowledge about the area and its users to make accurate assumptions. Therefore, conducting a load survey is the most suitable method for gathering data for GridVille.

A load survey offers several advantages, particularly for GridVille's context. It can be customized to meet the unique requirements and characteristics of the specific rural region in question, enhancing its flexibility. It is also a more economical approach, especially in rural areas where meter data access may be limited or non-existent. Moreover, a load survey is an engagement tool for GridVille to involve microgrid users, fostering an understanding of energy consumption patterns and rallying support for energy efficiency efforts.

GridVille can benefit from an existing model, such as RAMP mentioned in section 2.3.2 explicitly designed for remote and off-grid regions. The utilization of RAMP ensures that the resulting load profile accurately represents the energy demand of the microgrid, which is paramount for effective decision-making. RAMP also accommodates multiple energy sources and loads, considering the multifaceted nature of a microgrid.

Nevertheless, there are challenges associated with conducting a load survey. Data collection can be demanding and time-intensive, and data quality may be compromised, leading to incomplete or incorrect results that impact the load profile's accuracy. While involving the community in the process is advantageous for GridVille, it necessitates extensive community engagement and might still not fully represent the community's needs. Therefore, careful planning and execution of the survey are vital for GridVille to achieve the best outcomes. [13]

4.3 Type of Energy Source

Determining the energy source for a microgrid is a pivotal decision, significantly influencing its operation and longevity. Given GridVille's limited experience in microgrid development, initiating with a singular energy source might be beneficial before venturing into multiple sources. Past experiences from the initial year validate this approach as mentioned in section 3.3. Introducing multiple energy sources intensifies technical intricacies and adds administrative responsibilities, which could divert focus from the fundamental establishment phases. Thus, completing all phases with a single energy source could set a robust foundation for GridVille's efforts.

PV panels might be an apt choice for GridVille. PV panels, as mentioned in section 2.4, are known for their clean, renewable energy generation capabilities, easily blend into microgrid frameworks, and are well-suited for off-grid use in rural locations. Many regions lacking access to electricity are also characterized by high solar radiation, making PV panels an optimal choice for electrification initiatives.

In addition, PV systems offer several advantages, such as ease of installation and maintenance, scalability to cater to a community's energy requirements and durability. Over time, PV panels are likely to become more efficient, thus proving to be cost-effective in the long run. Furthermore, GridVille's strong association with Engineers Without Borders, renowned for constructing and implementing PV systems in Africa, provides invaluable experience and expertise to lean on during their microgrid ventures. Considering all these factors, PV panels are a good choice for GridVille as they aim to complete the phases.[13]

4.4 Type of Energy Storage

As mentioned in section 2.6, there are several options when choosing a storage device for a microgrid. Referring to section 2.6, it becomes evident that a BESS is the most suitable storage option for the microgrids GridVille intends to design. BESS aligns well with renewable energy sources, offers a reduced energy cost over its lifespan, is relatively compact, and can be conveniently installed in various settings.

However, choosing a specific type of BESS presents a more complex task. Table 2 represents the same table as Table 1 in section 2.6.5 based on GridVille's priorities.

Table 2: Design Considerations prioritized.

Battery Design Considerations		
Most important	**Fairly important**	**Least important**
Reliability Safety Lifetime Maintenance cost Initial cost	Installation cost BOP cost Environmental impact	Engineering cost Disposal cost Shipping cost

As observed in Table 2, prioritizing safety and reliability in selecting a battery type for GridVille's microgrid systems is paramount, mainly because students will interact with the system. It is crucial to guarantee the dependability of the chosen battery while also ensuring it presents no safety hazards. Likewise, the economic aspect of the battery selection needs careful consideration. It is vital to balance investing in a high-quality battery and keeping its cost from significantly influencing the project's overall budget.

However, choosing a specific type of BESS presents a more complex task. There is not a single solution that drastically outperforms the others in all circumstances. In the case of GridVille, lead-acid batteries emerge as the best solution. They are typically less expensive, demand less maintenance, and are broadly considered safer than other types. Since students conduct the system tests and design, safety should be a top priority when deciding on a BESS.

4.5 Use of MTF in GridVille

When sizing a microgrid, it is crucial to ensure that the system can meet the energy demands of the community it serves. However, as mentioned in section 2.7.2, these demands are not uniform and can vary significantly based on factors such as household size, income levels, and the availability of energy-efficient appliances. By utilizing the MTF, GridVille can better understand these variables and how they translate into actual energy needs.

For instance, a community predominantly at Tier 1 or 2 of the MTF may primarily require energy for essential lighting and mobile phone charging. In this case, a smaller microgrid focusing on reliable evening hours of operation may be sufficient. On the other hand, a community at Tier 3 or 4 community may have more substantial energy needs, including powering appliances like televisions or refrigerators. This would require a larger microgrid with a higher capacity and more robust infrastructure.

Moreover, the MTF can also guide the future expansion of GridVille's microgrids. As communities grow and develop, their energy needs will likely increase and move up the tiers. By regularly reassessing the community's tier level, GridVille can proactively plan for capacity upgrades to GridVille's microgrid, ensuring that it continues to meet the community's evolving energy needs. However, the first microgrid that GridVille produces will cover Tier 2 of the MTF.

5 Field Trip To Africa

Since student organizations like GridVille do not exist previously, it is not possible to travel and visit others with similar experiences. However, there is a wealth of knowledge in Africa and Asia that GridVille lacks. Sizing up a microgrid in Norway is not the same as sizing it up for a rural area that has never had electricity before. One of the key topics where GridVille lacks knowledge is the utilization of electricity.

GridVille has no experience in how a microgrid can be implemented in rural areas and how existing microgrids in developing countries are operated and maintained. Therefore, in conjunction with two other master's students from the Department of Electrical Energy, I have traveled to Tanzania and Kenya to gain an understanding and experience in the use of electrical energy in such areas and countries where GridVille would typically operate, as well as to comprehend the challenges these places face in electricity utilization. The field trip was three weeks long and went on from late April to the beginning of the May. All pictures in this chapter are taken by the author during this field trip, and everyone has consented to the use of the pictures.

5.1 Life and Electricity Usage on Tumabatu Island

Tumabatu Island is situated in the Kaskazini A District of the Lindi Region along Tanzania's Indian Ocean coastline. The Island is the native home of a sub-cultural group of the Hadimu known as Tumbatu. These individuals prefer to live in isolation, with minimal influence from both mainland Tanzania and Zanzibar. Normally, they do not welcome tourists and are not interested in outsiders entering their residential areas. However, with special permission granted by the tribal leader, we were allowed to visit the island and learn more about their way of life, how they utilize electricity in their daily routines, and any challenges they face.

They strive to preserve their traditions and values to the best of their abilities. Nevertheless, they seek to improve their quality of life and rely on electricity supply from the mainland. However, this electricity is expensive and unreliable due to inadequate infrastructure. As a result, several households have installed solar panels on their rooftops to provide lighting after sunset. Figure 15 and Figure 16 is pictures taken from the island.

Figure 15: Field trip at Tumbatu. [21]

Figure 16: In front of the hospital building at Tumbatu.[21]

There is also a small hospital on the island, which operates entirely on electricity generated from solar panels. This hospital is very modest in size and relies on electricity for lighting and basic medical equipment used by the doctor. The system and the hospital can be seen in the background in Figure 16.

5.2 Collaboration with Technical University of Mombasa

TUM is a public university located in a city called Mombasa and is one is the oldest institutions of higher learning in Kenya. TUM is divided into 5 different schools and institutes. The School of Engineering and Technology is one of them and currently offers a wide range of academic programs at undergraduate and postgraduate levels. Their goal is to educate students with the ability to apply theory to practice, research, and disseminate knowledge. The curricula are designed based on a foundation of integrated, systematic engineering knowledge.

The purpose of this visit where to understand the ways of both teaching and learning in Africa, to understand what problems they face with the utilization of energy, and to understand what their technical focus is and why. Another objective was to introduce and present GridVille to the teachers and deans and try to get an official collaboration with them. This meeting was hosted by Dr. Gideon Guyo Kidegho, Chairman of the Department (CoD) of Electrical and Electronic Engineering, accompanied by four fellow students from the Electrical Engineering department, as well as several professors at the university. These students are master students working with PV systems, microgrids, and energy utilization. Some of the one attended are presented in Figure 17.

Figure 17: The representatives at the meeting at TUM [21].

A significant amount of different information was shared during this meeting. One particular focus of TUM at the moment is the performance differences between solar panels with and without dust coating. In Africa and Asia, there is generally a higher presence of dust and sand in the air compared to other regions. This can be attributed to factors such as the lack of asphalt on roads, which are often replaced with sand and soil. Consequently, a layer of sand often accumulates on PV panels within a relatively short period, necessitating regular cleaning. One of the master's students at TUM is currently investigating this phenomenon as part of their thesis, aiming to determine the extent of the performance differences. Figure 18 and Figure 19 represents one of the systems set up by TUM, where half of the panels are cleaned while the other half remains unwashed.

Figure 18: Test setup at TUM [21].

Figure 19: From PV to this system [21].

By analyzing the data, they aim to quantify the impact, specifically in Africa. Since the analysis was not yet completed at the time of the visit, it is difficult to draw conclusive implications for GridVille. However, considering that the microgrid GridVille will deliver in the first couple of years is expected to be relatively small, catering to tier 1 and 2 appliances, it is logical to assume that they may not need to factor in this issue during the microgrid's design or operation. However, the importance of washing the panels occasionally is still there and should be conveyed by GridVille to the user.

Another point of discussion was the impact of heat on solar panels in Kenya. Another master's student has been studying the performance difference of PV panels based on the amount of wind in a country like Kenya for over a year. It has been observed that panels located closer to the coast in Kenya exhibit better performance compared to those further inland. However, it was quickly concluded that this factor is not particularly relevant for GridVille and will not make a difference in how GridVille designs its system.

Finally, one of the most significant points was discussed: energy usage. This topic was raised multiple times during the visit and was considered one of the biggest issues in Kenya, according to the locals. But could be observed in several places during the field trip. It revolves around the lack of discipline among users who consume electricity without considering the consequences. It was discussed that this may be attributed to various factors, one being the lack of adequate education and knowledge about how these systems actually work. Understanding why certain actions are allowed or restricted and the underlying framework can be challenging.

Several examples were provided of different microgrids and energy systems being overloaded due to users consuming more electricity than intended, connecting appliances that were not meant to be used with the system, or simply leaving appliances on simultaneously when they were not supposed to be.

This problem is highly complex and has no definitive solution, as this is not a technical problem. It highlights the importance of having a proper load profile. When GridVille implements the tool developed in this master's thesis, it is crucial to input the RAMP model with the most accurate information possible. This is because, after the microgrid is deployed, a strict framework can be established for how the users should utilize the microgrid. By having an accurate and detailed load profile, the microgrid can be properly sized. Any additional power consumption beyond this profile would then be due to misuse rather than insufficient power supply.

Several solutions were discussed for this issue. One of them could be establishing a centralized control system at GridVille that activates when the microgrid is overloaded, notifying the user that certain appliances must be unplugged before the microgrid can be restored.

Another solution could involve the use of timers or other smart devices controlled by GridVille, determining the operational periods of specific power extensions or outlets. Such devices are relatively inexpensive and would ensure that appliances are only used within the designated time slots. This also adds a certain level of automation to the system. For example, in the case of lighting, if it is intended to be used between 18:00 and 21:00, this schedule can be set on the smart plug. The lights will automatically turn on at 18:00 and off at 21:00. By implementing this approach; it eliminates the need for users to be near a power outlet to plug in a device, as everything happens automatically, while also mitigating the risk of overloading.

5.3 Off-grid Microgrid at Eco Moyo Education Center

The Dzunguni village is a modest rural village characterized by economic hardship, where the majority of residents live in mud houses lacking electricity and running water. A school named Eco Moyo Education Centre is located in this village and is a Norwegian/Kenyan charity project offering free primary education to children. In March 2022, Eco Moyo received a solar and battery off-grid, catering to the fundamental electricity requirements necessary for the school's operations. This microgrid configuration comprises seven solar panels and four batteries. The system provides power for appliances such as phones, a printer, a fan, and various other smaller devices. Table 3 presents components installed at Eco Moyo [10], [11].

Table 3: PV system installed at Eco Moyo in March 2022

Descrition	**Quantity**	**Capacity**	**Brand**
PV Panels	7	450 Wp	GCL
Inverter	1	3500 W	Growatt
Tubular Gel Battery	4	200Ah / 12V	Eastman (Chloride Solar)

The trip's primary purpose was to look at the system and observe user behavior and the operation of the existing system. The remarkable aspect of this microgrid is actually its over-dimensioned capacity relative to its usage during the visit. This system serves as a prime example of an oversized grid, which could have resulted in cost savings if it had been designed with fewer panels and batteries. A survey conducted by other master's students reveals that only about 1% of the energy in the grid at Eco Moyo is actually utilized.

The appliances used in this grid are listed in the Table 4.

The location data for eco moyo is listed in Table 5.

Table 4: Appliance Information

Appliance	**Power**	**f**	**req. tot**	**use**	**Window 1 mjik**	**Window 2 mjik**	**use**
Indoor LED	9	100	300	2	06:00-07:00	18:00-23:59	2
Outdoor LED	9	100	180	2	06:00-07:00	18:00-23:59	2
Phone	7	100	120	10	07:00-19:00	-	6
Laptop	60	100	120	8	07:00-19:00	-	4
TV	60	100	360	1	10:00-23:59	-	1
Decoder	8	100	360	1	10:00-23:59	-	1
Printer	200	50	30	1	07:00-19:00	-	-
Tablet	15	80	120	10	10:00-16:00	-	-

Table 5: Parameter Values

Parameter	**Value**
Latitude	3.5°S
Longitude	39.8°E
Altitude	58 m
Timezone	GMT+3
Slope	6.8°
Azimuth	-50°

5.4 Availability of Equipment and Appliances in Kilifi

To comprehend the dynamics of the non-European market, particularly concerning the acquisition of PV panels and batteries, as well as various appliances, an investigation was conducted during the field trip. Kilifi, a town situated 56 kilometers northeast of Mombasa, was found to have several small stores offering PV panels and batteries for SHS. These panels are offered in local shops by staff who may lack considerable expertise in this field and might not fully understand how everything functions appropriately.

The quality of the equipment was uncertain, with scarce information available about the products. While it is feasible for GridVille to source products from such local stores in the future, it is advised to be cognizant of the product origin, validate that the datasheet is accurate, and thoroughly test the product before it is left with the user. Figure 20 are taken at the market in Kilifi and represent some of the PV panels that were sold on the streets.

Figure 20: Market in Kilifi [21].

Regarding the usage of appliances, they are sold in various locations, in both small and large local stores, with varied experience. Insights gathered from this investigation indicate that many locations sell the same appliances with different power ratings. For example, a kettle could have a power rating ranging from 1500 W to 2500 W. Such a rating would influence how quickly, for instance, water boils in this case, but the amount of time this would take would probably not impact the grid user. Therefore, GridVille should participate in appliance purchases, especially in the initial phase. By doing this and performing accurate analyses on the potential power ratings of appliances available at the specific location, it becomes possible to ensure an accurate load profile as far as possible.

The quality of appliances is also a crucial factor. Not all appliances found on the market were of notably high quality. GridVille can aid in filtering out these at the beginning and assist in ensuring that the user possesses higher quality products that will last longer, but also will not potentially harm the microgrid they are designing.

6 Existing Programs and Custom Scripts

This chapter delves into the exploration of existing microgrid optimization tools and the advantages of developing a custom script for GridVille. It discusses the reasons why GridVille might consider creating its own optimization script, despite the availability of numerous software tools and scripts. The chapter also provides a comparative analysis of exisiting microgrid optimization software, including HOMER, PVSYST, Prosumpy, and GridSolve, highlighting their strengths and limitations in relation to GridVille's specific needs. Furthermore, we examine what constitutes a good tool in terms of accessibility and ease of use. We also explore the concept of good code structure and how to establish a custom tool.

6.1 Custom Sizing Script for GridVille

While numerous software tools and scripts are available for optimizing the design and operation of microgrids, there are compelling reasons for GridVille to consider developing its custom script.

6.1.1 Customization to GridVille's Needs

A custom script can be tailored specifically to GridVille's needs and requirements. This includes accommodating any unique or proprietary factors that need to be considered in the design and operation of the microgrids that GridVille develops. Many of these are mentioned in section 4. Unlike off-the-shelf software, a custom script can be adapted to meet specific needs and requirements, leading to more accurate, reliable, and effective optimization results. This customization ensures that the script aligns with GridVille's goals and objectives mentioned in section 3.

6.1.2 Flexibility

Developing a custom script allows GridVille to retain complete control and ownership over the tool, including its source code, data inputs, and output formats. This is particularly important for maintaining confidentiality and security and adapting the script to changing needs or technologies. It also avoids reliance on external software vendors, providing GridVille greater autonomy.

6.1.3 Learning and Development Opportunities

Creating a custom script provides valuable learning and development opportunities for GridVille members. It offers hands-on experience with coding, optimization, and microgrid design, fostering technical skills and expertise within the organization. This process can also foster a sense of ownership and engagement among its members, enhancing the overall team experience.

6.1.4 Longevity and Scalability

By creating their script, GridVille ensures they have a long-lived and scalable tool. A custom script can evolve and adapt as GridVille's needs and capabilities change, avoiding the risk of being tied to a specific software vendor or platform. By ensuring its longevity, it will not become outdated quickly. This enables the organization to maintain a high level of autonomy and independence.

6.1.5 Cost-Effectiveness

Depending on the licenses and fees associated with using existing software, developing their script may be a more cost-effective option for GridVille. While there are upfront costs associated with developing a custom script, these may be offset by the avoidance of ongoing licensing fees and the benefits of customization, control, and adaptability.

6.2 Overview of Existing Microgrid Optimization Tools

Various software programs and scripts have already been developed to determine the optimal sizing of microgrids. These tools typically offer user-friendly interfaces and a range of features and options to define microgrid components, loads, and constraints. Notable examples of specialized microgrid optimization software include HOMER, PVSYST, Prosumpy, and GridSolve. These programs facilitate the comprehensive analysis and design of microgrids, considering factors such as renewable energy sources, load profiles, storage capacity, and system constraints. This chapter briefly compares this software and empathizes with why GridVille needs a custom tool [44]–[47].

Flexibility:

Flexibility in software refers to how much the user can change or customize the software to suit their specific needs. Flexibility is crucial for a technical student organization like GridVille because it allows the team to adapt the software to the unique requirements of their off-grid microgrid projects. The more flexible the software, the more it can be tailored to handle specific scenarios, energy sources, and constraints the team may encounter. Table 6 compares the flexibility of the four software tools.

Table 6: Comparison of Flexibility. [44]–[47]

Software	Flexibility
HOMER [44]	High (User can change various parameters and constraints)
PVSYST [46]	Moderate (Significant data input and setup time required)
Microgrid Solver [47]	High (Can handle a wide range of microgrid configurations and scenarios)
Prosumpy [45]	High (User can change dispatch strategies)

Several energy sources:

The ability of a software tool to work with all energy sources is another crucial factor for GridVille. Off-grid microgrids often integrate various energy sources, such as solar, wind, and diesel generators, to ensure a reliable power supply. A software tool that models and optimizes all these energy sources provides the most comprehensive and realistic analysis. As mentioned in 4.3 GridVille will only deliver microgrids with PV panels during the first years. However, they still need the flexibility of using more energy sources for future use. Table 7 compares the four software tools in terms of their compatibility with all energy sources.

Table 7: Comparison of Compatibility with All Energy Sources.[44]–[47]

Software	Works with All Energy Sources
HOMER	Yes
PVSYST	No (Primarily for PV systems)
Microgrid Solver	Yes
Prosumpy	No (Primarily for PV and battery systems)

Off-grid microgrids:

Not all energy modeling software tools are designed for off-grid applications. Some are better suited for on-grid or grid-tied scenarios. However, GridVille focuses on off-grid microgrids, so the software they use must be specifically designed for or capable of handling off-grid scenarios. Table 8 compares the four software tools in terms of their suitability for off-grid microgrids.

Table 8: Comparison of Suitability for Off-grid Microgrids. [44]–[47]

Software	Suited for Off-grid Microgrids
HOMER	Highly suited (Designed specifically for off-grid microgrids)
PVSYST	Suited (Used for both on-grid and off-grid applications)
Microgrid Solver	Highly suited (Designed specifically for microgrids)
Prosumpy	Suited (Designed for self-consumption and solar home battery systems)

Technology majority:

Different software tools may specialize in or be better suited for different technologies or systems. For example, some might be specialists at modeling photovoltaic systems, while others focus more on hybrid or wind systems. Understanding the technology majority of a software tool can help GridVille choose the tool that is most aligned with the technologies they plan to use in their microgrids. Table 9 compares the technology majority of the four software tools.

Table 9: Comparison of Technology Majority. [44]–[47]

Software	Technology Majority
HOMER	Hybrid systems
PVSYST	PV systems
Microgrid Solver	Hybrid systems
Prosumpy	PV and battery systems

Price:

Price is a practical consideration for any organization, including GridVille. While some software tools are freely available, others require a commercial license. The cost of the software needs to be weighed against its features, capabilities, and value. Table 10 compares the four software tools in terms of price.

Table 10: Comparison of Price. [44]–[47]

Software	Price
HOMER	Commercial (Free trial available)
PVSYST	Commercial (Free trial available)
Microgrid Solver	Unknown
Prosumpy	Free (Open source)

Customization:

As mentioned in section 6.1.1, the ability to further develop and customize a software tool can be necessary for a technical student organization like GridVille. It allows the team to add new features or change the software to serve their specific needs better. This is especially valuable in a learning environment where students can gain hands-on experience in software development and customization. Table 11 compares the four software tools in terms of their potential for further development and customization.

Table 11: Comparison of Further Development and Customization. [44]–[47]

Software	**Further Development and Customization**
HOMER	Limited (Closed source)
PVSYST	Limited (Closed source)
Microgrid Solver	Unknown
Prosumpy	High (Open source, can be customized and further developed by users)

6.3 Comparative Analysis: Existing Tools and Custom Script Development for GridVille

Based on the discussions and comparisons made in this section, it is evident that developing a custom script for GridVille offers several advantages. These include customization to GridVille's specific needs, flexibility, learning and development opportunities for GridVille members, longevity and scalability, and cost-effectiveness.

While there are several existing microgrid optimization tools available, none of them fully cater to all of GridVille's requirements. For instance, while Prosumpy offers high flexibility and is free to use, it does not support all energy sources and is primarily designed for PV and battery systems. Despite this, Prosumpy's open-source nature and the ability for further development and customization make it a valuable source of inspiration for GridVille's custom script.

6.4 Accessibility and Ease of Use in a Custom Tool

The development of a user-friendly script and guide is a critical aspect of this project, given that the tool will be used by a diverse group of students with varying levels of prior knowledge and technical ability. Effective teaching involves more than just imparting knowledge; it also involves helping learners to understand, apply, and retain that knowledge. The tool should not only be functional but also accessible and easy to use for students. Given the varying levels of technical expertise among GridVille members, it's crucial to structure the script in a clear and intuitive manner. This approach will allow learners to understand the script more easily. Moreover, as it is expected that members of the organization will continue to build upon and modify the script to optimize its performance and improve its capabilities, the script should be designed in a modular and scalable manner. This will facilitate easy modification and expansion by future users.

In discussions with Per-Odd Eggen and Nils Kristian Rossing from The Resource Centre for mathematics science and technology in schools, NTNU's resource and competence center for teaching in natural sciences, it was suggested that structuring the code in a clear and organized manner, with examples of use for difficult codes and equations included in the code itself, would be beneficial. It was also advised to avoid using complex functions when simpler or more familiar functions that yield the same result are available. This approach will make the script more accessible to users with varying levels of coding expertise.

Interviews and discussions with current and former GridVille members highlighted the fact that learning styles are personal. Some members preferred a script with a lot of code included, while others preferred a separate document to explain the overall process. Some even suggested the use of a video explaining how the script works. This feedback underscores the importance of providing multiple resources to cater to different learning styles.

The language used in the script and guide should be simple and understandable for users with various levels of education. While it may be necessary to provide more explanation within the code than in a traditional code, it's important to strike a balance so that it is informative without being overwhelming. The script and guide are not products intended for sale or to look aesthetically pleasing, but rather tools to facilitate learning and application. Therefore, the language used should prioritize clarity and simplicity.

6.5 Emphasizing Good Coding Practices

The design and organization of a software program, often referred to as its coding architecture, is a fundamental aspect that influences the program's maintainability, scalability, and overall performance. A well-structured architecture can make a program more comprehensible, adaptable, and extendable, while a poorly structured one can lead to a program that is challenging to work with and prone to errors. Therefore, it's crucial for GridVille to carefully plan and consider the coding architecture of the program to ensure it aligns with the needs of its users and can be easily maintained and improved over time.

Data input is a critical aspect of any Python script. The choice between using Excel files or Comma Separated Values (CSV) files often depends on the specific requirements of the project. Excel files, due to their widespread use and easy editing capabilities, are often the go-to choice. However, as the volume of data grows, Excel files can become cumbersome and challenging to manage. On the other hand, CSV files, being lightweight and easy to read and parse, can be more efficient for handling large datasets. The choice between these two methods should be made considering the technical comfort level and familiarity of GridVille members.

Modules and packages in Python are self-contained units of code that can be imported and used in other scripts. They can be organized based on their functionality, such as data processing, optimization, or visualization. For GridVille's optimization script, the code could be organized into different modules and packages based on the different components of the microgrid, such as energy sources, loads, and controllers. This approach can lead to a more structured and organized codebase.

Consistent and descriptive naming conventions can significantly improve the readability and understandability of the code. For Python, common naming conventions include using lowercase letters, underscores, and digits for variable names, with words separated by underscores, and using CamelCase for class names. Adhering to these conventions can make the code more intuitive and easier to navigate for GridVille members.

7 Creating a Tool for GridVille

Based on the theory outlined in section 2, the design choices made in section 4, the experiences collected from the field trip described in section 5, and the guidelines for how a tool designed for students should be, as derived from section 6.5, a flowchart has been created, as represented in Figure 21 to illustrate the structure and interaction of the tool that is being made for GridVille.

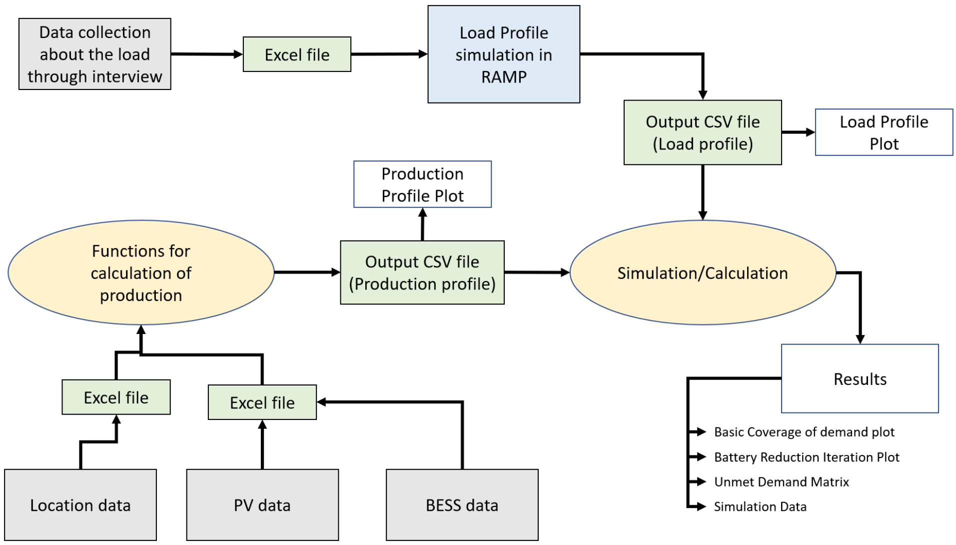

Figure 21: Flowchart describing different stages in the custom tool.

The RAMP method, as described in section 2.3.2, will extract the load profile. The tool will also generate a production profile based on the location data the user inputs. The tool allows the user to input PV panels and battery parameters. The method of creating the production profile is inspired by ProSumpy, as mentioned in section 6.2. Using both the production profile and the load profile, simulations are done with different plots to show the user of the tool different combinations of PV and batteries and how they cover the demand. The code is structured to give several options, not one optimal answer.

7.1 General Code Setup

The code is written in Python, and it is important to have Python installed on the machine to run the code. Additionally, specific Python packages are required to execute different functionalities within the code. These packages need to be downloaded and installed before running the code.

The code repository is organized into several scripts and modules, each serving a specific purpose in the microgrid sizing process. The key scripts and modules include:

- **main.py**: The main entry point for running the code and coordinating other scripts.
- **load_profile_run.py**: Handles the generation of multi-energy load profiles in off-grid areas using RAMP.
- **input_file_1.py**: Processes input data for load profiles, extracting user and appliance information from an Excel file. There are 4 files for this, each representing a season.
- **PV_production_data.py**: Processes input data for PV production, including reading Excel files and obtaining meteorological data from the PVGIS database.
- **Run_simulation.py**: Conducts simulations to determine the optimal number of PV panels and batteries needed to meet demand.

The execution of the code follows a defined flow. After ensuring the code is run from the correct directory, the main script verifies the threading setup to ensure proper execution. It also creates a **results** directory to store some of the output data.

The code then proceeds to execute the necessary functions and simulations for load profile generation (**load_profile_run.py**) and PV production data handling (**PV_production_data.py**). These steps involve reading and processing input data, performing calculations, and generating relevant plots and output files.

Finally, the code simulates determining the optimal number of PV panels and batteries by executing the **Run_simulation.py** script. This simulation iteratively adjusts the number of PV panels and batteries, calculates the unmet demand, and produces results and visualizations.

To ensure proper understanding and usage of the code, users are advised to read the provided **README.md** file outlines the project structure and provides guidance on running the code. A Microgrid Sizing guide in PDF format is also provided for further reference and assistance.

By following this methodology, the code for sizing off-grid microgrids is organized and flexible, enabling users to conduct simulations and obtain optimized microgrid size calculations for rural electrification projects.

One key feature of the code is its flexibility in usage. Users can run specific parts of the code based on their needs. For example, it is possible to simulate a load or production profile independently by providing the necessary data through third-party sources. Users can also execute only the simulations for calculating microgrid sizes, utilizing pre-generated load and production profiles.

7.2 Implementation of RAMP in the Tool

The tool should be designed so that it is easy to understand and use, even for those with limited prior experience or knowledge in this area. As described in section 3, GridVille comprises members who may not necessarily have technical backgrounds, e.g., some board members. The purpose of this tool is also for it to be utilized by individuals, such as the board members, in the planning phase. Therefore, the data acquisition process should be conducted in the simplest manner possible. This is where the use of Excel for data input comes into play.

The RAMP model, as described section 2.3.2, is a sophisticated tool for generating load profiles. However, it requires a certain level of technical expertise to use effectively. The model is structured around advanced Python classes and methods, which can be challenging for users unfamiliar with object-oriented programming.

In contrast, as mentioned in section 6.5, Excel is a widely used tool that most students are familiar with. It provides a user-friendly interface for entering and manipulating data and does not require any programming knowledge. By adopting the RAMP model to accept Excel inputs, the tool is more accessible to a broader range of users.

Moreover, by keeping the core RAMP model intact and only modifying the input method, we can maintain the model's reliability while improving user-friendliness. This approach allows us to leverage the robustness and sophistication of the RAMP model while also making it more accessible and user-friendly for the members of GridVille.

The original RAMP script is configured with input files that are individually retrieved. Users can choose the number of files they desire and specify the duration for each input file to exist. Each user must be registered with a code, and appliances need to be manually registered per user.

An example can be looked at employing input file 1. Within this file, to register a user, the registration process would be as follows:

```
# Regsitration of "Example building 1"
Example_1 = User("Example Building 1",1,3) #Registering a
    user.
User_list.append(RB1)
```

Furthermore, appliance registration is performed for each appliance following these steps:

```
#using r_t = 0.2, r_w = 0.35
```

```
Phone_example = Example_1.Appliance(Example_1
    ,6,7,1,2*60,0.2,5) #Appliance parameters
#time window: 07:00-23:59
Phone_example.windows([7*60,1439],r_w =0.35) #Defining
    the time window that the appliance is used
```

The user and the appliance are registered by defining several parameters and data. The parameters are explained in Appendix D. The process of entering both users and appliances in this manner is lengthy and demanding. Additionally, it is easy to make small errors that could result in non-functioning code. For instance, as mentioned in section 5.3, RAMP was used to make several load profiles for Eco Moyo. When creating a load profile with 26 users, 863 lines of code were written in just one of the input files to create one load profile for Eco Moyo.

As a result, the input files have been replaced with Excel spreadsheets in accordance with section 6.5 . There are now six sheets included in the same Excel document. The first sheet contains information and instructions on how to enter users and appliances. The second sheet, "User," is used for user registration. There is no longer a need to consider the input files. All users can be registered in the same sheet, regardless of which input file that user is being used in. The code is structured to iterate through the user and appliance lists independently, meaning there is no limit on how many appliances and users can be registered in the Excel document.

As shown in Figure 22, the Excel document is organized with four input sheets, one for each season. Users of the tool can modify this by adding or removing sheets, and making minor changes to the code to accommodate any changes. These modifications significantly simplify the usage of RAMP and make the tool more user-friendly, as discussed in section 6.5.

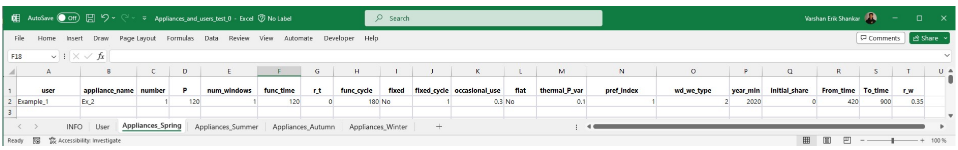

Figure 22: Example of ramp input Excel file.

7.3 Production Profile

In order to calculate the production profile, a code was developed to maximize flexibility, user-friendliness, and generalization for a broad range of use cases. The structure of the code takes advantage of several key libraries. The main ones are pvlib for photovoltaic system modeling, pandas for data manipulation, matplotlib for data visualization, and pytz for timezone management. The primary choice of libraries was due to its robust functionality and easy syntax, which makes the code more accessible for non-technical users.

The core of the code is divided into three main sections: data extraction, data processing, and data visualization. These steps correspond to the stages in the flowchart represented in Figure 21.

The function also calculates the cell temperature. Then, the dc output of the PV system is estimated. These choices of models were based on their balance of accuracy and computational efficiency. Furthermore, the code implements temporal shifts in the data to account for timezone differences and drops extra rows from the dataset to ensure consistency. This ensures that the resultant dataset corresponds accurately to local time.

The final stage of the code involves data visualization, where the computed DC output is saved as a CSV file and a PDF plot. Generating a CSV file allows users to access the raw data and is used for further calculation of the microgrid size. Meanwhile, the PDF plot provides a graphical representation of the DC power output, providing a clear and concise way for users to understand the performance of their PV system over time.

7.4 Calculation of Microgrid Size

In order to calculate the size of the microgrid and visualize the results, libraries such as pandas, numpy, matplotlib, and scipy are imported for data handling, calculations, and visualizations. The demand data is imported from a CSV file and adjusted to a 15-minute interval through linear interpolation. The unit of measurement is also converted from Wh to kWh for convenience. Similarly, PV production data is also imported from a CSV file, adjusted to a 15-minute interval, and normalized to 1kW.

The script then sets the battery parameters, including battery capacity, battery efficiency, inverter efficiency, timestep, the maximum power output of the inverter, and the battery's annual degradation rate. A list to store the state of charge for each time step is initialized. The total yearly energy demand is calculated and compared to the total yearly energy output from a single PV panel to determine the number of required PV panels. The maximum daily energy demand is also calculated. Considering battery degradation, efficiency, and minimum soc, the script calculates the number of batteries needed.

The script then uses a loop to calculate the net power at each time step, determine whether there is a power surplus or deficit, and adjust the state of charge of the batteries accordingly. The batteries are charged during a surplus, but not beyond their total capacity. During a deficit, the batteries are discharged, but not below the minimum state of charge. The state of charge is saved for each time step.

The script then creates two plots, one showing the power demand and production over time, and the other showing the batteries' state of charge over time. These plots are saved to a PDF file.

A function is defined to iteratively reduce the number of batteries until the percentage of unmet demand exceeds 5% compared to the initial simulation. For each number of batteries, it calculates the state of charge, total demand, and unmet demand at each time step and records these values in lists. It also creates plots showing the demand, production, and unmet demand over time, as well as the percentage of unmet demand for each number of batteries. The function returns a list of results, including the number of batteries, the percentage of unmet demand, and the lists of charge, discharge, and unmet demand.

The key function, iteratively_change_pv_and_batteries, takes an initial number of PV panels and batteries as input. For each potential configuration within a set range of these initial inputs, the function simulates the ability of the configuration to meet energy demand.

The simulation assumes that surplus power is used to charge batteries, and power deficits are covered by discharging batteries. If batteries are unable to cover the deficit, this leads to unmet demand. The function calculates the percentage of unmet demand by dividing the total unmet demand by the total demand and stores these values in a 2D matrix.

After running the simulation, the program visualizes the results in a heatmap using the matplotlib library. The x-axis represents the number of batteries, and the y-axis represents the number of PV panels. The color in each cell of the heatmap corresponds to the percentage of unmet demand, with green indicating 100% demand coverage (no unmet demand), and red indicating higher percentages of unmet demand. The specific percentage is also written in the center of each cell for precision.

This simulation and visualization allow users to understand the impact of varying numbers of PV panels and batteries' on-demand coverage. They can help in decision-making processes when considering the scale of an off-grid renewable energy system.

Further explanation on how this tool is built, including information about the needed packages, can be found in the README file provided in the code folder and with a copy in Appendix E.

Several different simulations were conducted to confirm the functionality of the code. These tests involved modifying the battery parameters, the load profile, or/and the production profile. Multiple tests were also performed with various combinations.

7.5 Sizing Example with Eco Moyo Education Center

In section 5.3, it is mentioned that the microgrid at Eco Moyo is significantly oversized. Therefore, examining this specific case using the tool developed is quite interesting. One of the main principles of the code is to avoid oversizing, therefore simulations were performed with a load profile containing the values mentioned in Table 12 and Table 13.

Table 12: Input data for the hot and warm seasons with high visitor activity [48].

				Weekdays			**Weekends**		
$Appliance_{jik}$	P_{jik}	$freq.$	tot_use_{jik}	m_{jik}	*Window 1*	*Window 2*	m_{jik}	*Window 1*	*Window 2*
Indoor LED	9	100	300	2	06:00-07:00	18:00-23:59	2	06:00-07:00	18:00-23:59
Outdoor LED	9	100	180	2	06:00-07:00	18:00-23:59	2	06:00-07:00	18:00-23:59
Phone	7	100	120	10	07:00-19:00	-	6	07:00-19:00	-
Laptop	60	100	120	8	07:00-19:00	-	4	07:00-19:00	-
TV	60	100	360	1	10:00-23:59	-	1	10:00-23:59	-
Decoder	8	100	360	1	10:00-23:59	-	1	10:00-23:59	-
Printer	200	50	30	1	07:00-19:00	-	-	-	-
Tablet	15	80	120	10	10:00-16:00	-	-	-	-

Table 13: Input data for the fan for different seasons [48].

				Window 1			tot_use_{jik}	
$Appliance_{jik}$	P_{jik}	$freq.$	m_{jik}	**Hot Season**	**Warm Season**	**Cold Season**	**Hot/Warm Season**	**Cold Season**
Fan	50	100	1	12:00-23:59	12:00-23:59	12:00-20:00	600	360

The battery was set to have the parameters shown in Table 14.

Table 14: BESS System Parameters

Parameters	Values	Units
Battery Capacity	2400	kWh
Battery Efficiency	0.9	-
Inverter Efficiency	0.93	-
Timestep	0.25	-
Max Power	3.5	kW
Battery Degradation	0.02	-

8 Results and Validation

The outcome of this master's thesis extends beyond a mere simulation. The results encompass the very code, methods, templates, and guidelines that have been developed. When constructing a code of this nature, validating it as thoroughly as possible is crucial. Therefore, this chapter will delve into the execution of the code under various scenarios, closely examine the output from the tool that has been crafted, and review the templates that have been established. The tool made for this master thesis, together with the forms and the guide, is uploaded on GitHub[1]. The guide is represented in Appendix F.

8.1 Load profile

Since the entire ramp model is based on interview data, the first step was to create a template for interviewing the grid user that needs to be sized. RAMP requires specific interview data and various parameters. To ensure clarity, this was taken into consideration along with some information that the user of the tool created can utilize before and during the interview to ensure that all necessary information for accurately calculating the load profile is included. By utilizing the knowledge and experience from the field trip described in section 5, and the structure of RAMP as described in section 2.3.2, the "*Off-grid system load profile assessment form*" was created. Figure 23 illustrates the table in the form and can be found in Appendix G.

Appliance Name	**Manufacturer**	**Quantity**	**Room**	**Prioritization**	**Usage pattern**	**Flexibility**
Example_1	No	5	Example_room_1	High	06:00-12:00 weekdays, 08:00-12:00 weekends.	No
Example_2	No	3	Example_room_1, Example_room_2	Medium	07:00-08:00 weekday	No
Example_3	No	2	Example_room_2	Low	18:00-20:00 every day.	Yes, can be moved by an hour both ways.

Figure 23: Figure representing the template of the Off-Grid System Load Profile Assessment Form found in Appendix G.

As mentioned in section 5, during the field trip, it was discussed that the load profile is not only about the user but also about the specific appliance and whether it is correctly chosen. The selection of the appropriate appliances can significantly

[1] https://github.com/varshan0104/SizingofOff_grid_microgrids

impact the load. Therefore, an "*Off-Grid System Appliance Assessment Form*" was created, as shown in Figure 24 and can be found in Appendix H.

Appliance Name	Manufacturer	Model	Energy Consumption	Vendor/Store	Price
Example_1	Samsung	Example	XXXW	Example AS	XX Dollar
Example_2	Sony	Example	XXXW	Example AS	XX Dollar
Example_3	Bosh	2	300W	Example_room_2	XX Dollar

Figure 24: Figure representing the template of the Off-Grid System Appliance Assessment Form found in Appendix H.

The information gathered from both Appendix G and Appendix G forms the foundation of the load profile. By inputting the data from these forms into the Excel sheet named "*Appliances_and_users*" located in "*.../Load_Profile/ramp/input_files*" a specific system's load profile is generated.

8.1.1 RAMP Validation

As mentioned in section 7.2, the approach used for data collection is different. To validate the code, random load profiles were created using the original RAMP file and the custom RAMP file designed explicitly for GridVille, which retrieves data through Excel. Figure 25 is a load profile calculated with the original ramp code.

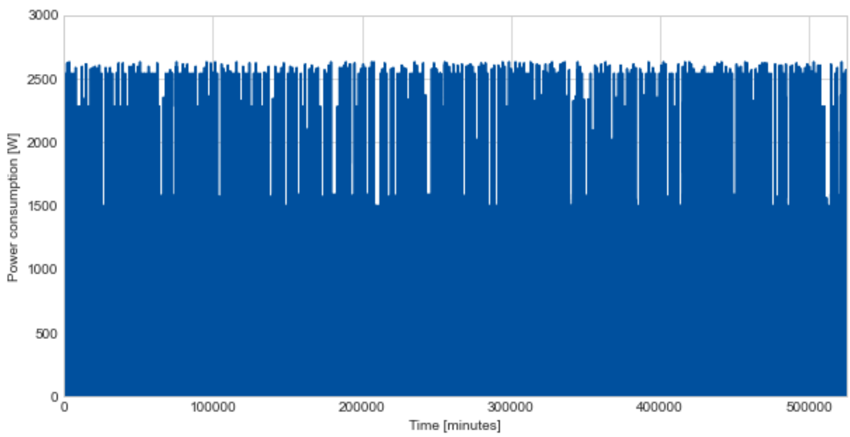

Figure 25: Load profile generated with the original RAMP code.

This load profile is generated for a year using only one input file, which means that there are no variations throughout the year that are also observed in the figure.

Figure 26 represents the same appliances and users calculated with the custom made tool.

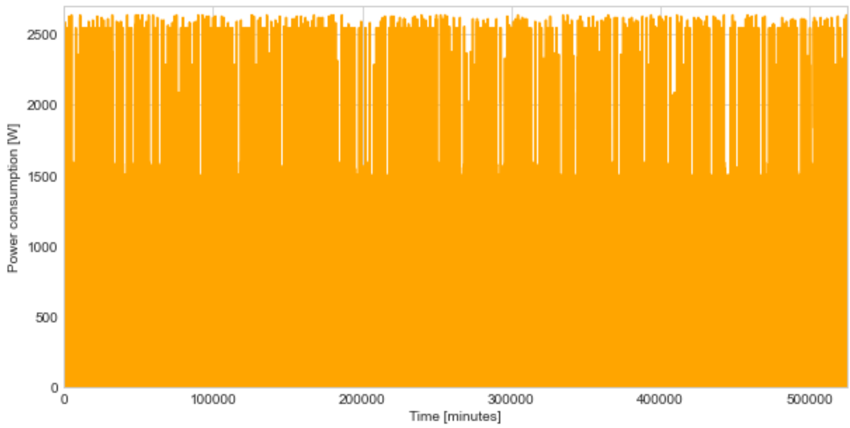

Figure 26: Load profile generated with the custom RAMP code.

Both Figure 25 and Figure 26 have 525 600 timesteps, with a total of around 256 004 kW when adding the power consumption for each timestep. Multiple simulations were conducted with different load profiles, and the results were consistent each time. Load profiles were also simulated using various input files. Figure 27 and Figure 28 include four input files. Figure 27 was simulated using the original RAMP code.

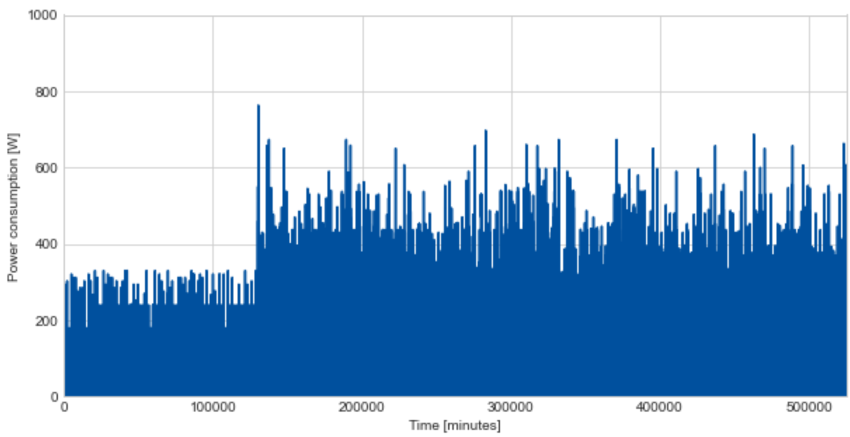

Figure 27: Generated with the original RAMP code and 4 input files.

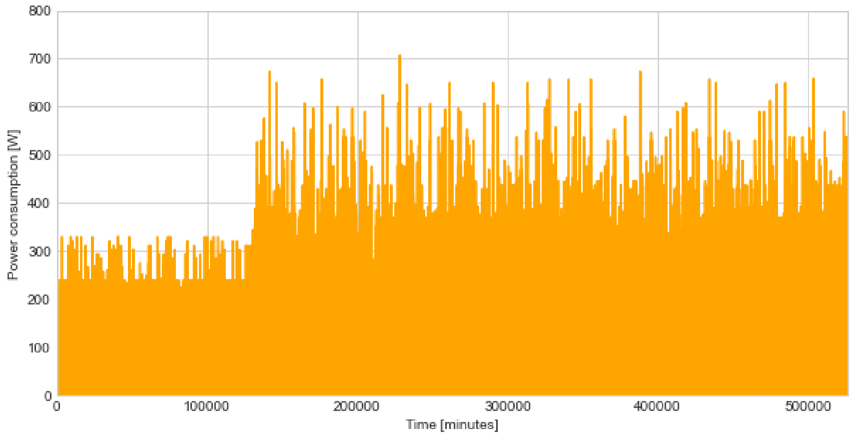

Figure 28: Generated with the custom RAMP code and 4 input files.

8.2 PV Production Profile

The data extraction is primarily accomplished via functions; **read_pv_data** and **read_location_data**. These functions accept an Excel file path and extract relevant data to be utilized later on in the code. The data extraction process takes a comprehensive set of PV parameters and location data from the Excel spreadsheet. This allows for detailed modeling of the PV system and provides flexibility in location-specific modeling. These functions then return Python dictionaries and Location objects, which can efficiently be utilized in subsequent stages of the code.

The **PV_production_data** function, provided in forms the heart of the data processing stage. It starts by calling the **read_pv_data** and **read_location_data** functions to extract the necessary data. It then manipulates and transforms this data to produce meaningful output. Specifically, it fetches the hourly solar irradiance data for the entire year using the PVGIS TMY tool. This tool provides typical meteorological year data, which can be used to estimate PV system performance.

To test the code for simulating the production profile, the technical parameters presented in Table 15 was used.

Table 15: PV Module Parameters

Parameters	Values	Units
P_{max}	450	W
v_{oc}	49.84	V
i_{sc}	11.34	A
α_{sc}	0.029904	A/°C
β_{voc}	-0.14952	V/°C
γ_{pmp}	-0.0039	A/°C
temp_{ref}	25	°C
$\text{surface}_{\text{tilt}}$	6.2	°
$\text{surface}_{\text{azimuth}}$	-50	°
price	100	$/unit

Figure 29 represents the solar production profile generated at Eco Moyo using the technical parameters presented in Table 15 and the location data presented in Table 5 in section 5.3. The code generating the production profile in the tool is named "**PV_production_data.py**" located in the folder "**Production_Profile**".

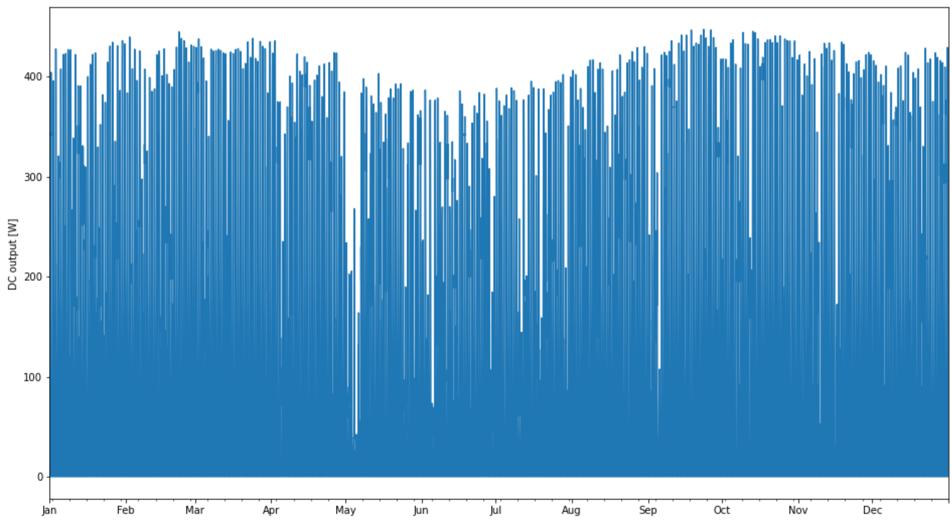

Figure 29: Solar production profile generated for Eco Moyo.

Several other production profiles were tested with different technical parameters and data to confirm the legitimacy of the code. Some of them are presented in Appendix I.

8.3 Sizing Simulation Example

As mentioned in section 7.4, several simulations were conducted to test the validity of the code. The results in this subsection refer to one of the more intriguing simulations conducted due to the disparities observed in the outcomes of simulations. These simulations included the parameters specified in the Table 16, as well as the production profile represented in Figure I.2 in Appendix I.

Table 16: BESS System Parameters

Parameters	Values	Units
Battery Capacity	2400	kWh
Battery Efficiency	0.9	-
Inverter Efficiency	0.93	-
Timestep	0.25	-
Max Power	3.5	kW
Battery Degradation	0.02	-

The result is shown in Figure 30, illustrating that 17 panels and 26 batteries are required to meet the general demand. These results are derived from the initial simulation, where no specific factors or optimization have been considered.

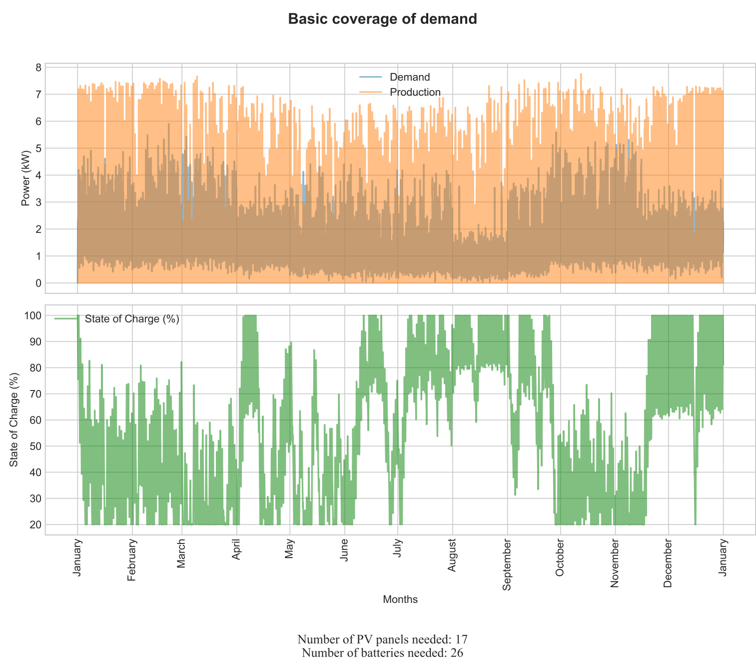

Figure 30: Basic coverage of demand example.

In the second simulation, as mentioned, the number of batteries was gradually reduced by 1 until the unmet demand reached 5% compared to the initial simulation. Ten iterations were performed in this case, and the graph for each simulation is presented in Appendix J. Every blue dot in the scatter plot represents one day that the demand was not met, as in Figure 31.

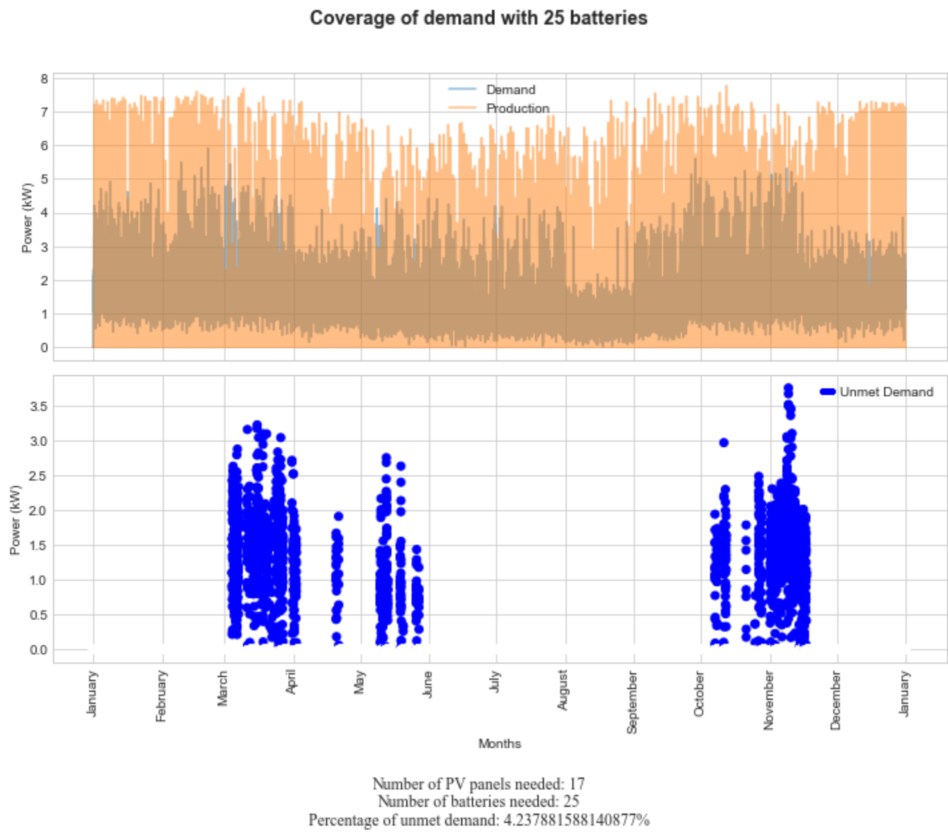

Figure 31: Coverage of demand with battery reduction itteration.

Several days between March and June can be observed where the demand is not met. The same happens between October and December. However, the total amount of unmet demand is 4.24%. Indicating that a really small amount is not being met during these months.

Subsequently, simulations were carried out with different combinations of batteries and panels. The results of these simulations are presented as a matrix in Figure 32.

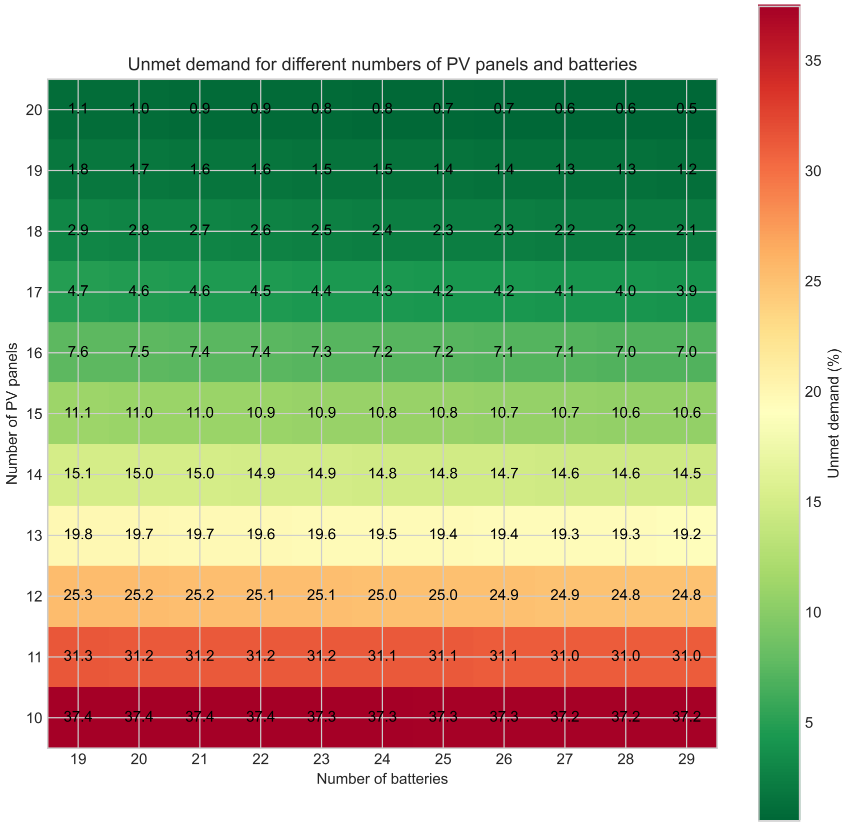

Figure 32: Matrix representing the unmet demand for different numbers of PV panels and batteries.

An interesting observation in Figure 30 indicates that 17 panels and 26 batteries are required to meet the energy demand. However, Figure 32 illustrates a 4.2% unmet demand at this combination.

8.4 Sizing Simulation Example on Eco Moyo

As mentioned in section 7.5, a simulation was conducted on Eco Moyo using the parameters specified in Tables Table 15 and Table 14, along with the load profile calculated with the appliances in Table 12 and Table 13, and the production profile depicted in Figure 29. Figure 33 illustrates the general coverage of this particular case.

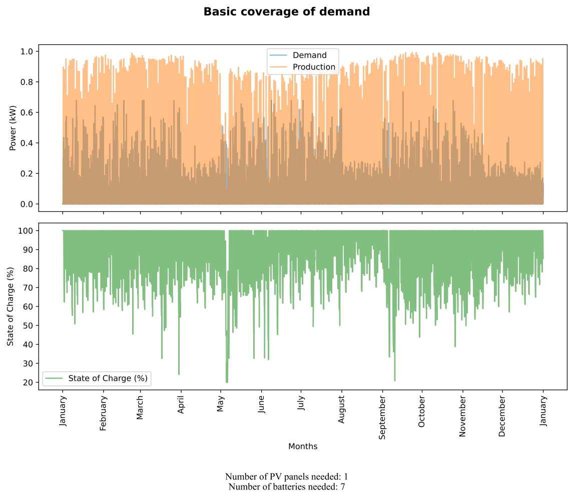

Figure 33: Basic coverage of demand at Eco Moyo.

Here, it can be observed that the code determines a requirement of 1 panel and 7 batteries. The following simulation is then executed, reducing the number of batteries. Figure 34 represents the battery count with 4 batteries.

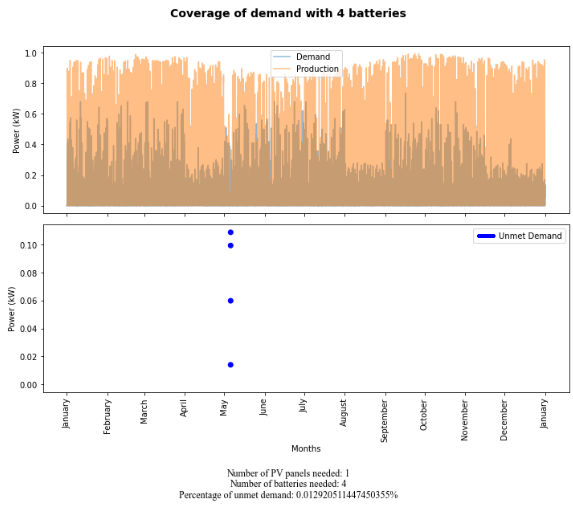

Figure 34: Coverage of demand at Eco Moyo with 4 batteries.

In this scenario, it can be observed that there are only 4 days in May throughout the year that are not covered, resulting in a total unmet demand of 0.01%. Figure 35 represents the same simulation with 2 batteries.

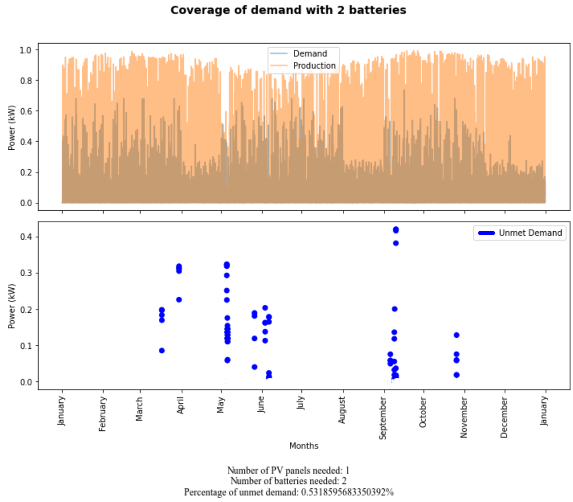

Figure 35: Coverage of demand at Eco Moyo with 2 batteries

Here, it can be observed that there are significantly more gaps, and there are more days when the demand is not met. Additionally, the unmet demand is now more spread throughout the year. However, it only accounts for a total of 0.5% of the demand. Figure 36 presents the unmet demand for different numbers of PV panels and batteries.

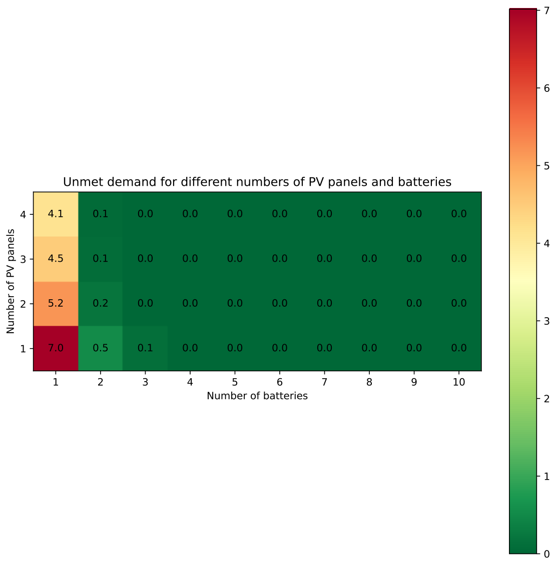

Figure 36: Unmet demand for different number of PV panels and batteries at Eco Moyo.

In this observation, it becomes evident that there are several alternatives to consider. As long as two or more batteries are available, it is possible to cover nearly all of the energy demand.

9 Discussion

This section discusses the tool developed for GridVille NTNU. It highlights the contribution of the master thesis to the SDGs, as well as discusses the coding structure of the tool, its user-friendliness, and potential areas for improvement. It validates the changes made to load profile generation and verifies the accuracy of the production profile. Furthermore, it delves into the extent to which this tool will assist in sizing an off-grid microgrid.

9.1 Sustainability

The work presented in this master thesis directly contributes to the achievement of several SDGs set forth by the United Nations. As described in section 1.1.2, GridVille is working towards addressing three of the SDGs. This master's thesis contributes similarly by directly and indirectly aiding GridVille in achieving these goals.

Firstly, it addresses SDG 1: "No Poverty". By developing a tool that enables GridVille to size and implement off-grid microgrids optimally, this work contributes to creating economic opportunities and improving living conditions in underserved communities. Access to electricity enables the establishment of businesses, enhances healthcare services, and facilitates educational opportunities, thus tackling poverty at its root. However, it is essential to note that without proper training and maintenance, these systems could fail, potentially exacerbating poverty levels, as experienced from the discussion at TUM during the field trip described in section 5.2.

Secondly, this thesis supports SDG 4: "Quality Education". Providing electricity to rural areas enables students to study beyond daylight hours, promotes technological tools for education, and helps bridge the educational divide. The knowledge foundation provided by this thesis will also enhance the technical skills of GridVille's members, contributing to their education and professional development. While electricity access can enhance educational opportunities, it is not a standalone solution. Other factors, such as the quality of teaching, availability of educational materials, and socio-cultural attitudes towards education, also play crucial roles.

Furthermore, this work contributes to SDG 7: "Affordable and Clean Energy". By designing and building microgrids powered by renewable energy sources, this thesis helps combat energy poverty and reduces dependence on fossil fuels. The tool developed in this thesis ensures that the microgrids are designed most efficiently and cost-effectively, making sustainable electricity more accessible to communities without access. It is, however, essential to consider the entire lifecycle of these systems. The production, transportation, and disposal of components like solar panels and batteries can have significant environmental impacts, and the community that gets the microgrid should, therefor, be educated on how to dispose of them.

Finally, the work in this thesis also indirectly contributes to other SDGs. For example, by enhancing access to electricity, it supports SDG 3: "Good Health and Well-being" by improving healthcare services, and SDG 8: "Decent Work and Economic Growth" by creating economic opportunities. However, these benefits are contingent on the microgrids' successful implementation and sustained operation. Challenges such as technical failures, lack of local expertise for maintenance, or changes in community dynamics could potentially limit these benefits. During the field trip, it became evident that energy utilization is a more significant problem than initially anticipated. Therefore, this should be one of the primary focus areas for GridVille in order to reach the SDGs.

9.2 Overall coding structure

The custom tool made for GridVille NTNU as part of this master thesis, demonstrates a good balance of simplicity, flexibility, and extensibility, indicating well-built code practices as mentioned in section 6.5. It follows best programming practices, such as a modular structure and clear function naming, making it easily understandable and modifiable, even for users with minimal technical knowledge. This makes it a perfect tool for diverse groups of users, including students in GridVille and board members who occasionally need to use it for budget planning or similar tasks.

From a user-friendliness perspective, the **README.md** file provides detailed explanations and instructions, making the project accessible even to users with limited technical knowledge. However, users need a basic understanding of Python and the required packages to run the scripts successfully.

The code can be used at three levels:

Basic level: GridVille members with little coding and technical knowledge can run the `main.py` file without making any changes to the code. They only need to modify the input parameters inside the Excel files. This level is helpful for small-budget planning or similar tasks.

Intermediate level: GridVille members with some coding knowledge can modify specific parameters and inputs, such as the number of iterations or the size of the simulations, to obtain more detailed or varied results. They can also activate or deactivate parameters specific to their particular simulation.

Advanced level: Technically adept GridVille members can delve deeper into the individual scripts, modify the underlying algorithms, or add new functionalities.

Another strength of this code is its capacity to handle a variety of scenarios and conditions. By allowing users to modify the input Excel files, the code can model different PV systems or consider location changes. This adaptability is crucial in the rapidly evolving field of renewable energy and microgrids that GridVille will work.

Furthermore, the code is structured to facilitate changes in system design by modifying relevant parameters. This modularity enhances readability and ease of future code extension, such as incorporating additional features or models.

While the code has many strong points, there are areas for improvement. Enhancing the code's user-friendliness could involve adding more extensive error handling and data validation steps. This would increase robustness and ease of use, particularly for non-technical users.

Regarding future development, the current code structure may pose challenges as it becomes more complex. As additional features or functionalities are added, significant restructuring may be required. Therefore, maintaining the code's modularity and navigability is crucial for its evolution and usefulness to diverse users.

The script could be enhanced for further development by incorporating more user-friendly interfaces or features. For example, a graphical user interface (GUI) could be developed to allow users to input parameters and run simulations without directly interacting with the code. This would make the script more accessible to non-technical users.

This script provides a strong foundation for a simulation tool that could be expanded with additional features, improved structure, and a more user-friendly design. It serves well as a tool for both technical and non-technical users, although improvements to lower the entry barrier for the latter group would be beneficial. Each script contains explicit comments explaining the purpose of each section, enhancing code understandability. The scripts adhere to good coding practices like modular design and readability.

The **main.py** script executes the other scripts sequentially, allowing step-by-step calculation and analysis of the microgrid sizing process. One key feature of the code is its flexibility in usage. Users can run specific parts of the code based on their needs. For example, it is possible to simulate a load or production profile independently. By providing the necessary data through third-party sources, users can also execute only the simulations for calculating microgrid sizes, utilizing pregenerated load and production profiles.

9.3 Validity of RAMP input change

In the context of the stochastic model used for load profile generation, it is interesting to note that while the underlying approach has not been altered, the way information is now retrieved is significantly different from the original model. This change is relevant when comparing the new method with the previous one, which is outlined in section 7.2 of the thesis.

The new method simplifies the process for the user, making it easier to specify which appliances are to be used at the location. It eliminates the need for the user to write numerous lines of code, thereby saving time and reducing the possibility of errors. This user-friendly approach is a significant improvement over the old method and contributes to the overall usability of the code. The interview data collection forms have been explicitly designed to align with how RAMP retrieves data. This enhances the usability of the tool, as the GridVille member conducting the analysis only needs to consider the forms given in Appendix G and Appendix H and does not need to refer to the code and Excel sheet.

By examining the generated load profiles provided in section 8.1.1 in detail. Evidently, the load profiles in Figure 25 and Figure 26 are not identical. This is particularly easy to observe around timestep 50 000 in the figure. Figure 25, for example, indicates slightly more load than Figure 26. This discrepancy can be attributed to the unique way the 'ramp' generates load profiles, as detailed in section 2.3.2.

Even without changes to the values or parameters, each simulation generates a unique load profile due to the randomness introduced when determining when appliances are used. As a result, there will always be some variation in the load profiles. However, given that the total energy consumption is nearly the same in both Figure 25 and Figure 26, it is reasonable to conclude that the load profile produced using the custom code is accurate.

The transformation in how appliance information is inputted and load profiles are generated has led to a more user-friendly experience while maintaining the accuracy and variability of the resulting load profiles. This shift signifies a considerable enhancement over the old method, boosting the overall effectiveness and usability of the code. The changes incorporated into this new method, combined with the insights gained from the load profile comparisons, reinforce the value of this code in simulating realistic energy usage patterns for GridVille. The same applies to the load profiles simulated with different input files. Even though Figure 27 and Figure 28 are not identical, is it evident to say that the differences are due to the nature of the stochastic model and not because errors in the code.

9.4 Production Profile Verification

When it comes to validating the accuracy of the production profile, a direct comparison with a production profile used in a previous master thesis [11] for Eco Moyo reference provides a reliable method. The data acquisition is quite similar between these two methods, but a substantial difference sets the tool created for GridVille apart: the level of automation.

In the context of GridVille, the code is designed to automatically fetch PV data, a feature that significantly enhances the user experience. The user is not required to manually download anything from the internet, which saves time and reduces the chance of errors that may occur during the manual data acquisition process. This automatic data retrieval is a significant improvement compared to ProSumpy mentioned in section 6.2, making the code more robust and user-friendly.

This automation does not compromise the accuracy of the production profile. By comparing the results from the GridVille tool with those used in another master thesis written for Eco Moyo [11], we can confidently state that the production profiles generated by the GridVille code align well with the reference data.

Therefore, the GridVille tool successfully streamlines the process of generating production profiles while ensuring the accuracy and reliability of the resulting data. This feature makes the tool highly valuable for users.

9.5 Simulation Results and Their Interpretation

The first step in the simulation results is to provide a basic overview of the system's coverage. This involves determining the number of energy storage systems required to meet the energy production when there is production and the number needed to cover when there is no production. This initial visualization is an essential first step in understanding the system's dynamics and sets the stage for more detailed analyses.

However, the results can vary significantly depending on several factors. The variation in the results is influenced by factors such as weather conditions affecting solar energy production, changes in energy demand throughout the day, and the energy storage systems' capacity and SoC. It is worth noting that these variations do not necessarily indicate inaccuracies or inconsistencies in the simulation but rather reflect the inherent complexities and uncertainties associated with energy production and consumption.

One handy feature of the simulation output is the visualization of the SoC. This provides valuable insights into the operation of the energy storage systems, including their charging and discharging patterns, how effectively they are meeting the energy demand, and how they interact with energy production. By observing the SoC, users can identify potential issues such as periods of overproduction or underproduction, and make necessary adjustments.

However, there may be some limitations associated with these visualizations. For some users, the detail provided by these graphs may be overwhelming, especially for those members of GridVille who are not familiar with energy system dynamics or are only interested in a high-level overview, e.g., budget planning. Moreover, it might be challenging to derive actionable insights from these graphs without a solid understanding of what each feature represents. It is thus essential to present this data in a manner that can be easily interpreted by all users, irrespective of their technical background.

While these graphs provide a wealth of information, their practicality for users might be improved by offering the option to customize the level of detail displayed or providing additional explanations or summaries of the results. However, it is essential to note that this trade-off between detail and usability is a common challenge in the design of simulation tools, as mentioned in section 6.2, and the most effective solution will depend on the specific needs and preferences of the users.

9.6 Analysis of Simulation Example Results

In analyzing and interpreting the simulation results, it is vital to delve deeper into the nuances underpinning the data. The initial simulation presented in Figure 30 suggested a configuration of 17 solar panels and 26 batteries to meet the demand. This determination was based on the strategy that calculated the total yearly energy demand and the maximum daily demand to size the PV system and the battery storage, respectively. While relatively straightforward and easy to comprehend, this method does not account for the temporal dynamics of energy supply and demand within smaller time frames.

On the other hand, the heatmap presented in Figure 32 presents a more nuanced view. It assesses how each configuration performs throughout the year by iteratively simulating different combinations of solar panels and batteries. The percentage of unmet demand is calculated for each scenario, providing a richer perspective of the system's performance.

Even though the configuration proposed by the first simulation (17 panels and 26 batteries) was based on sound logic, the heatmap reveals about 4.2% unmet demand with this setup. This discrepancy can arise due to the stochastic nature of solar energy production and demand. Energy production from solar panels depends on the variable sunlight exposure, which is influenced by weather conditions and seasonal variations. Likewise, energy demand is not constant, varying based on human activities, time of day, and season.

In other words, while the total annual energy production might match or even exceed the total annual energy demand, there can still be periods where the energy demand outstrips the available energy from the PV and battery system, resulting in unmet demand. This is particularly likely to happen during periods of high demand combined with low solar production, such as during the night or on cloudy winter days. Similarly, even with a battery storage system, there may be prolonged low solar production periods where the battery system gets fully depleted before it can be recharged.

Therefore, while the simplistic approach of the first simulation provides a good starting point, the more detailed analysis performed for the heatmap reveals the complexities and challenges of designing an energy system solely based on PV and battery storage. It underlines the need for more sophisticated analysis and potential supplementary strategies, such as demand response or energy conservation. Therefore, it is advantageous that the code calculates the size in various ways, allowing the user of the tool to decide which combination to pursue based on GridVille's priorities or specific focus during the simulated case.

9.7 Comperative Analysis of Eco Moyo Example

Delving into the specific case of Eco Moyo, an existing system with 7 solar panels and 4 batteries, presents a fascinating case study of the complexities and nuances of real-world energy system planning and performance. The initial basic coverage simulation presented in Figure 33 suggested a configuration of 1 solar panel and 7 batteries to cover the demand.

However, the heatmap presented in Figure 36, which iteratively simulates different combinations of solar panels and batteries, provides a richer perspective. It is clear that there are several combinations of panels and batteries that can potentially meet the demand, each with varying degrees of unmet demand. This opens up a whole spectrum of alternatives and possibilities.

The heatmap shows that the percentage of unmet demand is zero when considering the existing system at Eco Moyo, with 7 panels and 4 batteries. This means that with the existing setup, the system can cover all the demand. This suggests that the system's capacity is well-matched with the energy demand. This is evident in this specific case, as mentioned in section 5.3, where only a tiny fraction of the energy is utilized in relation to the size of the microgrid.

This highlights the importance of battery storage in off-grid solar PV systems. While more solar panels can increase the total energy generation, the excess energy generated during sunny periods could be wasted without adequate storage. Conversely, having more batteries but not enough solar panels might not necessarily decrease the unmet demand. The optimal combination would depend on various factors, including the pattern and magnitude of energy demand, the local solar radiation, the budget, and the physical space available for installing the panels or batteries.

Moreover, the results from the heatmap also underline the importance of considering other strategies to improve the system's performance. For example, implementing demand response measures to shift some of the energy demand to sunny periods, improving energy efficiency to reduce the total energy demand, or exploring if there is another need for electricity at the location that they also can provide for.

9.8 Analysis of the Custom Tool

The provided simulation methodology offers an innovative approach to effectively size off-grid PV systems, helping to avoid over-dimensioning while maintaining an acceptable level of energy service. It can be a valuable tool for decision-making in off-grid PV system planning and design.

The process begins with a basic coverage simulation that takes a simplistic yet practical approach to system sizing. It uses the total yearly energy demand to determine the number of PV panels and the maximum daily demand to calculate the necessary battery storage. This method provides an initial estimate of the system size needed to meet the demand. However, it does not consider the dynamics and variability of the demand and the PV production. In many cases, the system sized in this way could be over-dimensioned, leading to unnecessary capital investment.

The methodology then iteratively reduces the number of batteries and simulates the system's performance, aiming to find the minimum number of batteries needed without exceeding a specified threshold of unmet demand. It is an excellent technique for potentially identifying more cost-effective solutions than those provided by the basic coverage simulation.

Finally, the methodology runs an iterative simulation over various numbers of PV panels and batteries, creating a matrix that shows the percentage of unmet demand for each combination. It gives a comprehensive overview of how different system configurations perform, providing the freedom to choose an optimal balance between the system's cost and the level of energy service provided.

It is noteworthy that this methodology doesn't only help in avoiding over-dimensioning. It also highlights the importance of the balance between PV panels and batteries in system performance. A system might have a surplus of panels, but the excess energy generated might not be fully utilized if it lacks adequate battery storage. Likewise, an abundance of batteries without enough PV panels to charge them may not significantly reduce unmet demand.

The simulation methodology presented here provides a robust and flexible tool for sizing off-grid solar PV systems. It combines simplicity with detail, providing an accessible starting point and a thorough analysis of different system configurations. By avoiding over-dimensioning, it can help to make off-grid solar PV systems more economically viable and attractive for rural electrification, contributing to the sustainable development and energy access goals that GridVille has.

While the methodology presented here offers a robust and detailed approach to off-grid PV system sizing, it is important to note potential limitations. One possible shortcoming is that the tool has not been tested extensively with many users. So far, the validation of the methodology has been primarily performed by the author and a select group of individuals within the GridVille team. While undoubtedly valuable, this approach might not fully expose the tool to the wide array of knowledge and experiences that potential users might bring. Users with different backgrounds, ranging from students to professionals in the field, could uncover nuances and edge cases that have not been considered.

Moreover, such users could provide valuable feedback and insights, which could be instrumental in further refining and enhancing the tool. Different users use tools differently, which could help identify potential improvements to the user interface, the tool's flexibility, or its functionality.

10 Conclusion

This Master's thesis comprehensively explored rural electrification, focusing on designing and implementing a microgrid for the technical student organization GridVille NTNU. A Python-based tool was created through a systematic review of relevant literature, field experiences, and iterative development, designed to size microgrids in rural, off-grid areas. The tool incorporates various variables and constraints and utilizes a multi-objective optimization approach to produce practical and reliable solutions tailored to GridVille's needs.

The field experiences, particularly from Kenya and Tanzania, underscored the importance of understanding the local context, engaging with the community, and educating users about energy utilization. These experiences significantly informed the tool's development, ensuring its relevance to real-world scenarios.

The importance of considering various design aspects, such as the type of microgrid, energy source, and energy storage, was emphasized. PV panels were identified as an optimal energy source due to their suitability for off-grid environments, ease of installation, and scalability. Battery Energy Storage Systems (BESS), particularly lead-acid batteries, were endorsed due to their cost-effectiveness, safety, and reliability.

Through developing a practical tool for microgrid sizing, comprehensive insights into design choices, and detailed field experiences, this thesis makes significant contributions to rural electrification. It assists GridVille and similar organizations in their mission to bring sustainable and reliable electricity to off-grid, rural communities.

The simulation methodology begins with a basic coverage simulation for system sizing and an initial estimate. This simplistic yet practical approach uses total yearly energy demand and maximum daily demand to determine the necessary PV panels and battery storage. Furthermore, the methodology iteratively reduces the number of batteries, simulating system performance to find a minimum number that does not exceed a specified threshold of unmet demand. This technique may identify more cost-effective solutions than the basic coverage simulation. Additionally, the methodology runs iterative simulations over various PV panels and batteries, providing a comprehensive overview of how different system configurations perform. All these results allow the user to analyze based on their specific need and situation and choose the optimal microgrid setup for that particular project.

Despite these contributions, this thesis is merely the beginning. Further research is needed to refine and adapt the tool to the evolving technological landscape. GridVille gains more experience deploying and operating microgrids, and as more data becomes available, the tool can be updated to reflect these advancements. This ongoing learning, refining, and implementation process is vital to the success of rural electrification efforts, bringing us closer to the goal of universal electricity access.

In conclusion, this thesis has successfully developed a robust and accurate tool for sizing off-grid microgrids, providing a solid knowledge foundation for GridVille's technical members. It has highlighted the importance of custom solutions and deep theoretical understanding in addressing complex real-world challenges, promoting sustainable development, and improving quality of life. The work presented here serves as a crucial stepping stone in GridVille's journey towards making a significant impact in the global effort to combat electricity inaccessibility, contributing to the achievement of several UN Sustainable Development Goals.

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Appendix

A Overview of Technical Organization

Table A.1: Overview of technical organizations at the Norwegian University of Science and Technology.

Name	Established	Technology	Website
Ascend	Unknown	Drone	[49]
Fuel Fighter	2020	Energy-efficient electric car	[9]
GridVille	2021	Microgrid	[5]
Orbit	Unknow	Satelite	[3]
Propulse	2019	Rocket	[50]
Revolve	2012	Electric Racecar	[4]
Shift Hyperloop	2019	Hyperloop	[51]
Vortex	2016	Underwater drones	[52]

B PV Modelling Equations

The fill factor (FF) equation describes the efficiency of a PV system, which is the ratio of the maximum power output to the theoretical maximum power output.

$$FF = \frac{P_{max}}{V_{oc} I_{sc}} \tag{14}$$

where P_{max} is the maximum power output of the PV system (in Watts), V_{oc} is the open-circuit voltage (in Volts), and I_{sc} is the short-circuit current (in Amperes).

The temperature coefficient equation describes the effect of temperature on the performance of a PV system, including the impact on the short-circuit current, open-circuit voltage, and power output.

$$P_{max} = V_{oc} \cdot I_{sc} \cdot \left(1 - \frac{I_{ph}}{I_{sc}}\right) \tag{15}$$

The shading loss equation: This equation describes the impact of shading on the performance of a PV system, including the reduction in power output due to shading on individual modules or the entire array.

$$\alpha = \frac{1}{V_{oc}} \frac{dV_{oc}}{dT} \tag{16}$$

where α is the temperature coefficient, V_{oc} is the open-circuit voltage, and T is the temperature in degrees Celsius.

C Personal Experience

Extracurricular activities

GridVille

Jun 2021 - Ongoing   Trondheim, Norway

Technical Consultant

Part-time   May 2022 – June 2023

As the organization is still in its second year, it is still developing. New members and the board need guidance with technical and organizational work. I act as a technical consultant who answers questions frequently, as well as have weekly meetings to keep track of their progress.

Chief Electrical Engineer

Full-time   Jun 2021- May 2022

Together with 7 other students, we have created the first student project uniting sustainable power production and technical aid. We work with a microgrid that will supply electricity to a local community. I was responsible for the electrical part of the project. Among other things, this involves designing and analyzing DC/DC, AC/DC, and DC/AC converters as well as dimensioning the grid and control system.

Revolve

May 2020 – Aug 2021   Trondheim, Norway

Group Leader, Aerodynamics

Full-time

I was responsible for the external and internal flow of the car. Through advanced CFD analysis with supercomputer named Fram, we developed an effective and lightweight aerodynamic package, using high-lift wings, the underbody, as well as the car itself, to create downforce. Most components consist of composites that our group itself produces. This entails an area of responsibility of composite structure and layup, and design of fastenings of the group's components to monocoque.

Experience

Siemens

Sept 2022 – June 2023   Trondheim, Norway

Market Research Analyst

Part-time

Student worker in eMobility within the smart infrastructure department at Siemens. My responsibilities are to do market research and analysis of EV,EUV and other electric vehicle charging infrastructure (with a focus on software solutions). I also do competitor analysis, as well as some other minor tasks connected to eMobility.

NTNU Centre for Sport Facilities and Technology

May 2022 – Dec 2022   Trondheim/ Oslo Norway

Researcher, Electrification of motorsport in Norway

Part-time

Rudskogen, the national center for motorsport in Norway, is to be electrified. My role is to explore the possibilities for this. Create a load profile and charging structure, as well as calculate the size of both the grid and the battery system. My technical focus points change from week to week.

COWI

Jun 2022 – Aug 2022   Trondheim, Norway

Summer Intern

Seasonal

I spent 70% of my time as a technical consultant and designer for the new hospital Nordmøre and Romsdal. While 30% of my time is spent working on a solar collection project for Fossen Utvikling AS on Tanberghøgda in Hønefoss.

D RAMP Input Parameters

User(**name**, **n_users**, **us_pref**)

name = the name of the user

n_users = the number of users within the class

us_pref = allows to check if random number coincides with user preference, to distinguish between various appliance use options (e.g. different cooking options)

Appliance(**user**, **number**, **P**, **num_windows**, **func_time**, **r_t**, **func_cycle**, **fixed**, **fixed_cycle**, **occasional_use**, **flat**, **thermal_P_var**, **pref_index**, **wd_we_type**, **year_min**, **initial_share**)

user = user to which the appliance is bounded

number = number of appliances of the specified kind

P = power of the specified appliance

num_windows = number of functioning windows to be considered

func_time = total time the appliance is on during the day

r_t = percentage of total use that is subject to random variability

func_cycle = minimum time the appliance is kept on after switch-on event

fixed = if yes all the n appliances is kept on after switch-on event

fixed_cycle = if equal to 1, 2 or 3, respectively 1, 2 or 3 duty cycles can be modelled for different periods of the day.

occasional_use = probability that the appliance is always (every day) included in the mix of appliances that the user actually switches-on during the day

flat = allows to model appliances that are not subject to any kind of random variability, such as public lighting

thermal_P_var = allows to randomly variate the App power within a range

pref_index = defines preference index for association with random User daily preference behavior

wd_we_type = defines if the App is associated with weekdays or weekends | 0 is wd 1 is we 2 is all week

year_min = defines the first year in which the appliance can start to exist

initial_share = defines the initial share of ownership of the appliance among users of the class

E README file

README.md

Sizing of Off-Grid Microgrids

This repository contains Python scripts for sizing off-grid microgrids. This project is part of a master's thesis on the optimal sizing of off-grid microgrids, run under GridVille NTNU.

Getting Started

To get started, clone the repository and install the required Python packages.

Before running the code, ensure that you're in the correct directory. The directory should be `...SizingOff_grid_microgrids`.

Prerequisites

- Python: The code is written in Python. Make sure you have it installed on your machine.
- Packages: This project requires specific Python packages. The packages required for each script are detailed in their respective sections below. Make sure to install all necessary packages before running the code.
- Data files: The project uses data from specific Excel and CSV files. The files required for each script are detailed in their respective sections below. Make sure these files are correctly formatted and in the correct locations.

Execution

The code can be run by executing the `main.py` file.

If everything is set up correctly, it should print "This is the main thread" to the console. If you see the message "This is not the main thread", then the threading is not set up correctly.

The program also creates a `results` directory if it doesn't already exist, where the results of the computation can be stored.

Scripts

The repository contains the following scripts:

1. Main Script
2. Import Module
3. Load Profile Generation
4. Input Data Handling
5. PV Production Data Handling
6. Simulation Run

Prerequisites

1. **Python:** The code is written in Python. Make sure you have it installed on your machine.
2. **Packages:** This project requires specific Python packages. Ensure you've installed all necessary packages before running the code.

```
import os
import threading
```

3. **Data files:** The project uses data from specific Excel files. Ensure the "Appliances_and_users" Excel file in the directory `Load_Profile/ramp/input_files` is filled out.

Execution

The code can be run by executing the `main.py` file.

If everything is set up correctly, it should print "This is the main thread" to the console. If you see the message "This is not the main thread", then the threading is not set up correctly.

The program also creates a `results` directory if it doesn't already exist, where the results of the computation can be stored.

Modules

There are several components to this codebase:

- `load_profile`: This function (currently commented out) is likely responsible for handling load profiles.
- `PV_production_data`: This function appears to handle photovoltaic production data.
- `Run_simulation.py`: The code from this file is being read and executed. Make sure this file exists in the `Production_Profile` directory.

Note

There's a section of the code that's commented out, which seems to involve analysis functions. If you plan to use this part of the code, make sure you uncomment it and that all the necessary data files and functions are available.

Author

The codebase was developed by Varshan Erik Shankar as part of his master's thesis.

Import Module

In addition to the main script, the project also includes a module for importing product data. This module, `importproductdata.py`, contains the following functions:

- `read_pv_data(file_path)`: This function reads data from an Excel file about photovoltaic (PV) panels. It returns a dictionary of technical data and a nested dictionary for each PV panel's data.
- `read_battery_data(file_path)`: This function reads data from an Excel file about batteries. It returns a list of battery data.
- `read_location_data(file_path)`: This function reads location data from an Excel file. It returns a `Location` object (from the `pvlib` library) containing the latitude, longitude, timezone, and altitude of the location.

Prerequisites

To run `importproductdata.py`, you'll need the following Python packages:

```
import pandas as pd
import pytz
from pvlib.location import Location
```

Data Files

The `importproductdata.py` module expects Excel files with specific sheet names and formats. For each function, the Excel file should have:

- `read_pv_data(file_path)`: A sheet named 'PV' with columns for each PV panel and a row for each parameter.
- `read_battery_data(file_path)`: A sheet named 'Battery' with columns for each battery type and a row for each parameter.
- `read_location_data(file_path)`: A sheet named 'Location' with columns 'latitude', 'longitude', 'timezone', and 'altitude'.

Load Profile Generation

The module `load_profile_run.py` is part of an open-source stochastic model, RAMP, for the generation of multi-energy load profiles in off-grid areas.

Authors

This module was created by:

- Francesco Lombardi, Politecnico di Milano
- Sergio Balderrama, Université de Liège
- Sylvain Quoilin, KU Leuven
- Emanuela Colombo, Politecnico di Milano

Prerequisites

To run `load_profile_run.py`, you'll need the following Python packages:

```
import sys
import os
import numpy as np
import pandas as pd
```

Function

The main function in this module is `load_profile()`, which generates a total number of specified days' load profiles, post-processes the results, generates plots, and saves the data in CSV files in the results folder.

The function considers several input files, which are Python scripts defined as numbers in a list. The number of days a load profile for each input file will have is defined in a dictionary. The function then calls the stochastic process and saves the results in a list of stochastic profiles.

The `load_profile()` function also depends on two other modules: `stochastic_process` and `post_process`. Make sure these modules are accessible and correctly functioning.

Input Data Handling

The module `input_file_1.py` reads and processes input data for the load profiles. The data is read from an Excel file, `Appliances_and_users.xlsx`, which contains user and appliance information.

Prerequisites

To run `input_file_1.py`, you'll need the following Python packages:

```
import pandas as pd
from ramp.core.core import User, np
```

Functionality

The module contains the function `appliance_iterate(df2, User_list)`, which iterates over the rows of the 'Appliances_Spring' sheet in the Excel file, creating a list of user-appliance data. The function returns three lists: one for appliance data, one for user data, and one for time window data.

The module also creates a User object for each user, stored in User_list. Each User object also has an Appliance object, representing the appliances the user uses.

Data Files

The `input_file_1.py` module expects an Excel file with the name `Appliances_and_users.xlsx`, which should contain two sheets: 'User' and 'Appliances_Spring'.

The 'User' sheet should have columns 'user', 'n_users', and 'us_pref'. The 'Appliances_Spring' sheet should have the columns 'user', 'appliance_name', 'number', 'P', 'num_windows', 'func_time', 'r_t', 'func_cycle', 'fixed', 'fixed_cycle', 'occasional_use', 'flat', 'thermal_P_var', 'pref_index', 'wd_we_type', 'year_min', 'initial_share', 'From_time', 'To_time', 'r_w'.

PV Production Data Handling

The module `PV_production_data.py` processes input data for photovoltaic (PV) production and creates a plot of the DC output.

Prerequisites

To run `PV_production_data.py`, you'll need the following Python packages:

```
import pvlib
from pvlib.iotools import get_pvgis_tmy
import pandas as pd
import matplotlib.pyplot as plt
import pytz
from pvlib.location import Location
```

Functionality

The main function in this module is `PV_production_data()`, which reads PV data from an Excel file `productdata.xlsx` and location data from another Excel file `Locationandload_data.xlsx` using the `read_pv_data(file_path)` and `read_location_data(file_path)` functions respectively.

The function then obtains meteorological data from the PVGIS database for the given location, processes this data into the format required by pvlib, calculates the module temperature using the Faiman model, and calculates the DC output of the PV system using the PVWatts model.

The final DC output data is saved in a CSV file `pvlib_result.csv`, and a plot of the DC output is created and saved as a PDF file `results/DCoutput.pdf`.

Data Files

The `PV_production_data.py` module expects two Excel files:

- `productdata.xlsx` which should have a sheet named 'PV' with the following columns: 'P_max', 'v_oc', 'i_sc', 'alpha_sc', 'beta_voc', 'gamma_pmp', 'temp_ref', 'surface_tilt', 'surface_azimuth'.
- `Locationandload_data.xlsx` which should have a sheet named 'Location' with the following columns: 'latitude', 'longitude', 'timezone', 'altitude'.

Simulation Run

The module `Run_simulation.py` runs a simulation to determine the optimal number of photovoltaic (PV) panels and batteries needed to meet demand.

Prerequisites

To run `Run_simulation.py`, you'll need the following Python packages:

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.dates as mdates
import scipy.optimize as optimize
```

Functionality

The module first reads demand data from `Load_Profile/ramp/results/output_file_ecomoyu.csv` and PV production data from `pvlib_result.csv`. It then calculates the total energy demand and the total energy output from a PV panel for a year.

Based on these values, the module calculates the number of PV panels and batteries needed. It also calculates the battery's state of charge at each time step, as well as the battery charge and discharge.

After these initial calculations, the module runs a simulation that iteratively reduces the number of batteries and calculates the percentage of unmet demand. The results are plotted.

The module also contains a function, `iteratively_change_pv_and_batteries(num_pv_initial, num_batteries_initial)`, which runs a simulation for different numbers of PV panels and batteries and plots the results.

Data Files

The `Run_simulation.py` module expects two CSV files:

- `Load_Profile/ramp/results/output_file_ecomoyu.csv` which should contain the load profile.
- `pvlib_result.csv` which should contain the PV production data.

F Guide Made for the User of the Tool

Guide

Design Consideration for Sizing of Off-Grid Microgrid

Author:
Varshan Erik Shankar

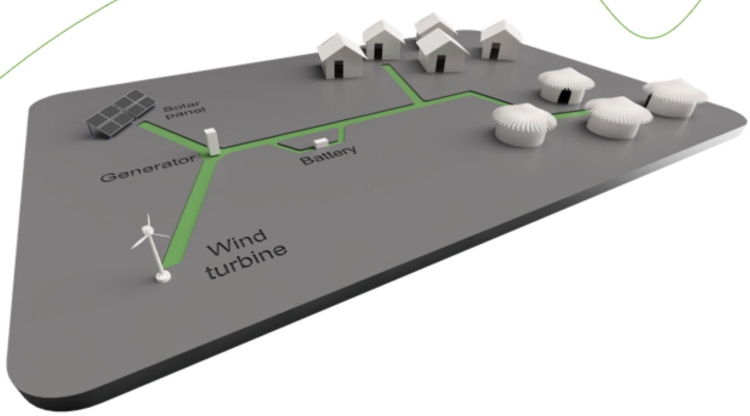
GridVille

Note!

This guide is based on a master thesis written for the Department of Electric Energy at NTNU. Please read the master thesis for elaborative information.

Sizing of Off-grid Microgrid

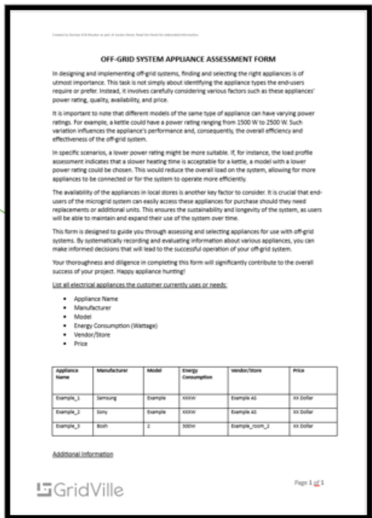
This tool is created for the sizing of off-grid microgrids, specifically for GridVille. It consists of three different simulations. Please refer to the README.md file to understand the structure of the code. It is possible to use only parts of the functions in this code. For example, if you have a CSV file with either a load profile or PV production, you can simply input that file and run only the "run_simulation" function to obtain the desired results. The intention of this code is not to provide an optimal answer regarding the number of solar panels and batteries needed. The main purpose is for users to make their own assessments based on the results, taking into consideration the specific situation and requirements of the grid being designed for.



Load profile

The model is built up using a interview model to collect information for the load profile. It is advised to look into similar areas with the same culture to understand microgrid options that already exists.

Use the **OFF-GRID SYSTEM LOAD PROFILE ASSESSMENT FORM** and the **OFF-GRID SYSTEM APPLIANCE ASSESSMENT FORM** located in this folder.



OFF-GRID SYSTEM APPLIANCE ASSESSMENT FORM

In designing and implementing off-grid systems, finding and selecting the right appliances is of utmost importance. This task is not simply about identifying the appliance types the end-users require or prefer. Instead, it involves carefully considering various factors such as these appliances' power rating, quality, availability, and price.

It is important to note that different models of the same type of appliance can have varying power ratings. For example, a kettle could have a power rating ranging from 1500 W to 2500 W. Such variation influences the appliance's performance and, consequently, the overall efficiency and effectiveness of the off-grid system.

In specific scenarios, a lower power rating might be more suitable. If, for instance, the load profile assessment indicates that a slower heating time is acceptable for a kettle, a model with a lower power rating could be chosen. This would reduce the overall load on the system, allowing for more appliances to be connected or for the system to operate more efficiently.

The availability of the appliances in local stores is another key factor to consider. It is crucial that end-users of the microgrid system can easily access these appliances for purchase should they need replacements or additional units. This ensures the sustainability and longevity of the system, as users will be able to maintain and expand their use of the system over time.

This form is designed to guide you through assessing and selecting appliances for use with off-grid systems. By systematically recording and evaluating information about various appliances, you can make informed decisions that will lead to the successful operation of your off-grid system.

Your thoroughness and diligence in completing this form will significantly contribute to the overall success of your project. Happy appliance hunting!

List all electrical appliances the customer currently uses or needs:

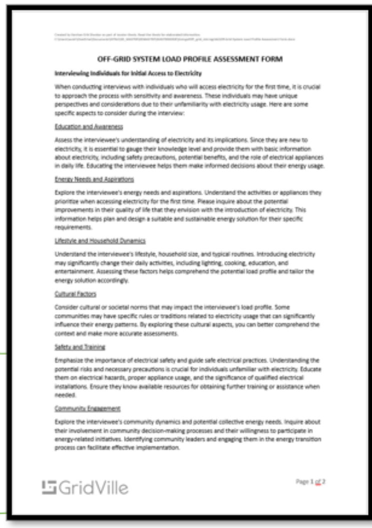
- Appliance Name
- Manufacturer
- Model
- Energy Consumption (Wattage)
- Vendor/Store
- Price

Appliance Name	Manufacturer	Model	Energy Consumption	Vendor/Store	Price
Example_1	Samsung	Example	XXXW	Example AS	XX Dollar
Example_2	Sony	Example	XXXW	Example AS	XX Dollar
Example_3	Bosh	2	300W	Example_room_2	XX Dollar

Additional information

GridVille

Page 1 of 1



OFF-GRID SYSTEM LOAD PROFILE ASSESSMENT FORM

Interviewing Individuals for Initial Access to Electricity

When conducting interviews with individuals who will access electricity for the first time, it is crucial to approach the process with sensitivity and awareness. These individuals may have unique perspectives and considerations due to their unfamiliarity with electricity usage. Here are some specific aspects to consider during the interview:

Education and Awareness

Assess the interviewee's understanding of electricity and its implications. Since they are new to electricity, it is essential to gauge their knowledge level and provide them with basic information about electricity, including safety precautions, potential benefits, and the role of electrical appliances in daily life. Educating the interviewee helps them make informed decisions about their energy usage.

Energy Needs and Aspirations

Explore the interviewee's energy needs and aspirations. Understand the activities or appliances they prioritize when accessing electricity for the first time. Please inquire about the potential improvements in their quality of life that they envision with the introduction of electricity. This information helps plan and design a suitable and sustainable energy solution for their specific requirements.

Lifestyle and Household Dynamics

Understand the interviewee's lifestyle, household size, and typical routines. Introducing electricity may significantly change their daily activities, including lighting, cooking, education, and entertainment. Assessing these factors helps comprehend the potential load profile and tailor the energy solution accordingly.

Cultural Factors

Consider cultural or societal norms that may impact the interviewee's load profile. Some communities may have specific rules or traditions related to electricity usage that can significantly influence their energy patterns. By exploring these cultural aspects, you can better comprehend the context and make more accurate assessments.

Safety and Training

Emphasize the importance of electrical safety and guide safe electrical practices. Understanding the potential risks and necessary precautions is crucial for individuals unfamiliar with electricity. Educate them on electrical hazards, proper appliance usage, and the significance of qualified electrical installations. Ensure they know available resources for obtaining further training or assistance when needed.

Community Engagement

Explore the interviewee's community dynamics and potential collective energy needs. Inquire about their involvement in community decision-making processes and their willingness to participate in energy-related initiatives. Identifying community leaders and engaging them in the energy transition process can facilitate effective implementation.

GridVille

Page 1 of 2

Input data into the "Appliances_and_users. xlsx" excel file. Make sure to look at the info sheet to understand the function. Located in ...\Load_Profile\ramp\input_files.

Page 4 of 8

Location Information

Use a website to find location data; Latitude and Longitude. E.g. https://www.latlong.net/.

Use a altitude map to find the altitude. E.g. https://www.daftlogic.com/projects-find-elevation-on-map.htm

Fill in the "location_data.xlsx" excel file and fill in the information. Make sure to chose the correct timezone.

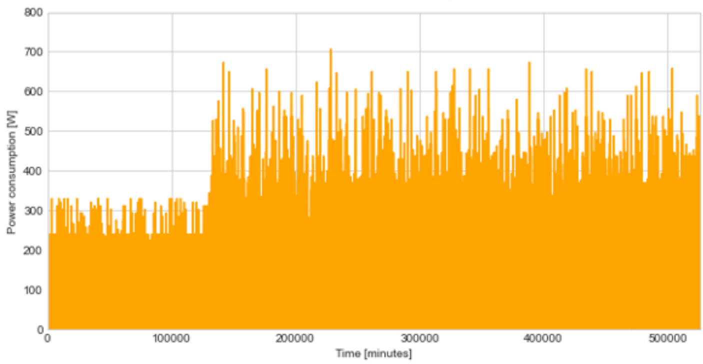
Product Information

Look into the data sheet of both the PV and the battery and make sure to fill in the "productdata.xlsx" correctly.

Load Profile

This code uses a model called RAMP to run the code. Read the master thesis for elaborated information.

Example result:



Output file:

Output_file_1

Output_file_1

Output_file_1

Output_file_1

Output_file_aggregated

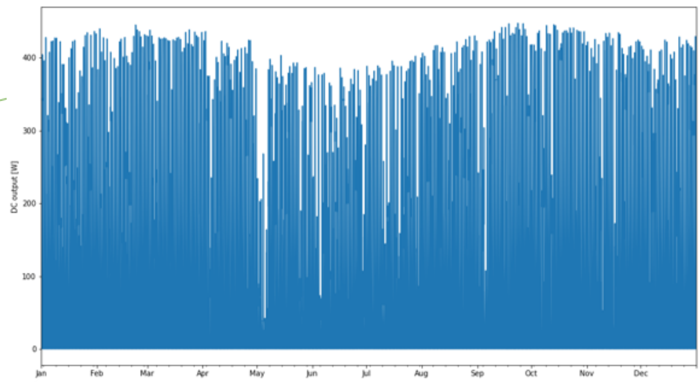
Example files located in the .../Load_Profile/ramp/results folder with name:

- *"Output_file_aggregated_example"*
- *"Output_file_ecomovo_staff_room"*

Solar Production Profile

Make sure to fill in location data and PV data before running this code.

Example result:



Output file:

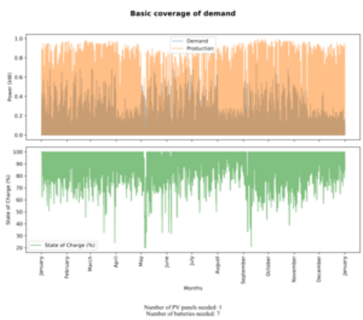
Pvlib_result

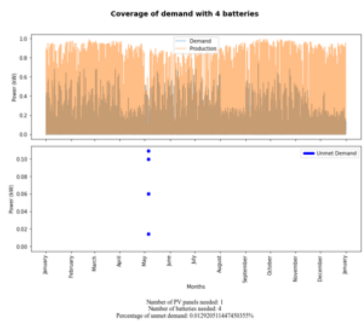
Run simulation

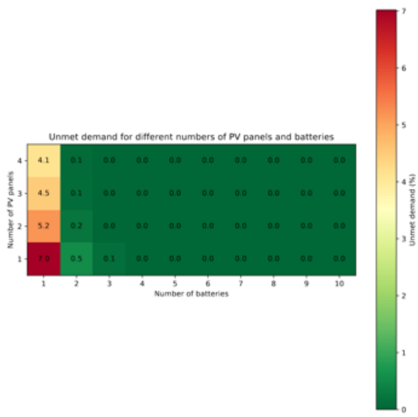
Make sure to have battery data filled out and a csv file with both PV data and Load Profile Data.

This can take some time to run. Depending on the size of the microgrid, and the parameters you choose to include.

Example output:







G Off-Grid System Load Profile Assessment Form

Created by Varshan Erik Shankar as part of master thesis. Read the thesis for elaborated information.

OFF-GRID SYSTEM LOAD PROFILE ASSESSMENT FORM

Interviewing Individuals for Initial Access to Electricity

When conducting interviews with individuals who will access electricity for the first time, it is crucial to approach the process with sensitivity and awareness. These individuals may have unique perspectives and considerations due to their unfamiliarity with electricity usage. Here are some specific aspects to consider during the interview:

<u>Education and Awareness</u>

Assess the interviewee's understanding of electricity and its implications. Since they are new to electricity, it is essential to gauge their knowledge level and provide them with basic information about electricity, including safety precautions, potential benefits, and the role of electrical appliances in daily life. Educating the interviewee helps them make informed decisions about their energy usage.

<u>Energy Needs and Aspirations</u>

Explore the interviewee's energy needs and aspirations. Understand the activities or appliances they prioritize when accessing electricity for the first time. Please inquire about the potential improvements in their quality of life that they envision with the introduction of electricity. This information helps plan and design a suitable and sustainable energy solution for their specific requirements.

<u>Lifestyle and Household Dynamics</u>

Understand the interviewee's lifestyle, household size, and typical routines. Introducing electricity may significantly change their daily activities, including lighting, cooking, education, and entertainment. Assessing these factors helps comprehend the potential load profile and tailor the energy solution accordingly.

<u>Cultural Factors</u>

Consider cultural or societal norms that may impact the interviewee's load profile. Some communities may have specific rules or traditions related to electricity usage that can significantly influence their energy patterns. By exploring these cultural aspects, you can better comprehend the context and make more accurate assessments.

<u>Safety and Training</u>

Emphasize the importance of electrical safety and guide safe electrical practices. Understanding the potential risks and necessary precautions is crucial for individuals unfamiliar with electricity. Educate them on electrical hazards, proper appliance usage, and the significance of qualified electrical installations. Ensure they know available resources for obtaining further training or assistance when needed.

<u>Community Engagement</u>

Explore the interviewee's community dynamics and potential collective energy needs. Inquire about their involvement in community decision-making processes and their willingness to participate in energy-related initiatives. Identifying community leaders and engaging them in the energy transition process can facilitate effective implementation.

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Page **1** of **2**

Created by Varshan Erik Shankar as part of master thesis. Read the thesis for elaborated information.
C:\Users\varsh\OneDrive\Documents\NTNU\00_MASTER\00MASTER\MASTERKODE\Sizingofoff_grid_microgrids\Off-Grid System Load Profile Assessment Form.docx

Interviewed by:

User Information

Name:

Location:

Contact information:

Energy Consumption and Appliance Information

List of room:

- User Name

Room Name
Example_room_1
Example_room_2

List all electrical appliances the customer currently uses or needs:

- Appliance Name
- Manufacturer (if any preference)
- Quantity
- Room/Location (where the appliance will be used)
- Prioritization (High/Medium/Low)
- Usage pattern (When and how often the appliance will be used) (Doesn't have to mean the appliance is used all the time or during the whole duration)
- Flexibility (Is the customer flexible about when and how to use this appliance)

Appliance Name	Manufacturer	Quantity	Room	Prioritization	Usage pattern	Flexibility
Example_1	No	5	Example_room_1	High	06:00-12:00 weekdays, 08:00-12:00 weekends.	No
Example_2	No	3	Example_room_1, Example_room_2	Medium	07:00-08:00 weekday	No
Example_3	No	2	Example_room_2	Low	18:00-20:00 every day.	Yes, can be moved by an hour both ways.

Additional Information

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Page 2 of 2

H Off-Grid System Appliance Assessment Form

Created by Varshan Erik Shankar as part of master thesis. Read the thesis for elaborated information.

OFF-GRID SYSTEM APPLIANCE ASSESSMENT FORM

In designing and implementing off-grid systems, finding and selecting the right appliances is of utmost importance. This task is not simply about identifying the appliance types the end-users require or prefer. Instead, it involves carefully considering various factors such as these appliances' power rating, quality, availability, and price.

It is important to note that different models of the same type of appliance can have varying power ratings. For example, a kettle could have a power rating ranging from 1500 W to 2500 W. Such variation influences the appliance's performance and, consequently, the overall efficiency and effectiveness of the off-grid system.

In specific scenarios, a lower power rating might be more suitable. If, for instance, the load profile assessment indicates that a slower heating time is acceptable for a kettle, a model with a lower power rating could be chosen. This would reduce the overall load on the system, allowing for more appliances to be connected or for the system to operate more efficiently.

The availability of the appliances in local stores is another key factor to consider. It is crucial that end-users of the microgrid system can easily access these appliances for purchase should they need replacements or additional units. This ensures the sustainability and longevity of the system, as users will be able to maintain and expand their use of the system over time.

This form is designed to guide you through assessing and selecting appliances for use with off-grid systems. By systematically recording and evaluating information about various appliances, you can make informed decisions that will lead to the successful operation of your off-grid system.

Your thoroughness and diligence in completing this form will significantly contribute to the overall success of your project. Happy appliance hunting!

<u>List all electrical appliances the customer currently uses or needs:</u>

- Appliance Name
- Manufacturer
- Model
- Energy Consumption (Wattage)
- Vendor/Store
- Price

Appliance Name	Manufacturer	Model	Energy Consumption	Vendor/Store	Price
Example_1	Samsung	Example	XXXW	Example AS	XX Dollar
Example_2	Sony	Example	XXXW	Example AS	XX Dollar
Example_3	Bosh	2	300W	Example_room_2	XX Dollar

<u>Additional Information</u>

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Page **1** of **1**

I Solar Production Data Examples

Different technical paramteres and location data was tested to make solar production profiles with the custom code.

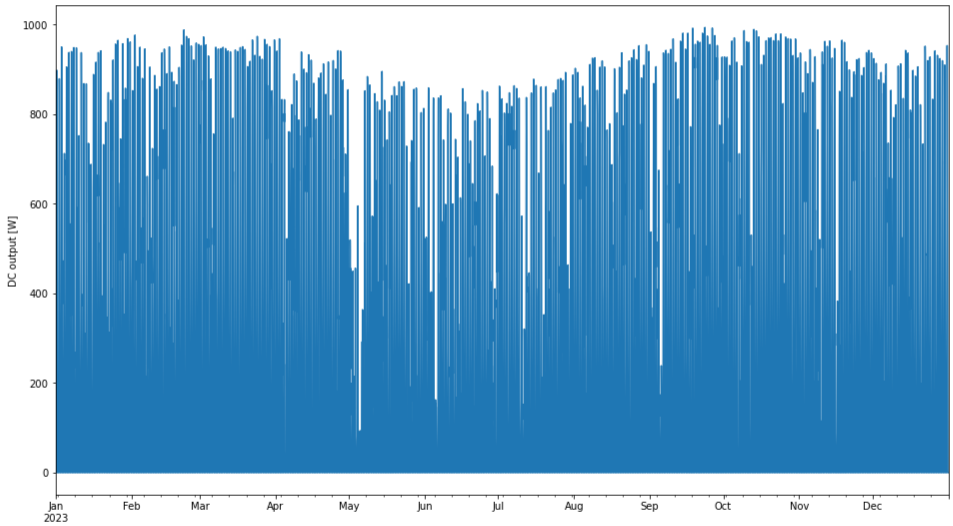


Figure I.1: Eco Moyo production profile with different PV paramter.

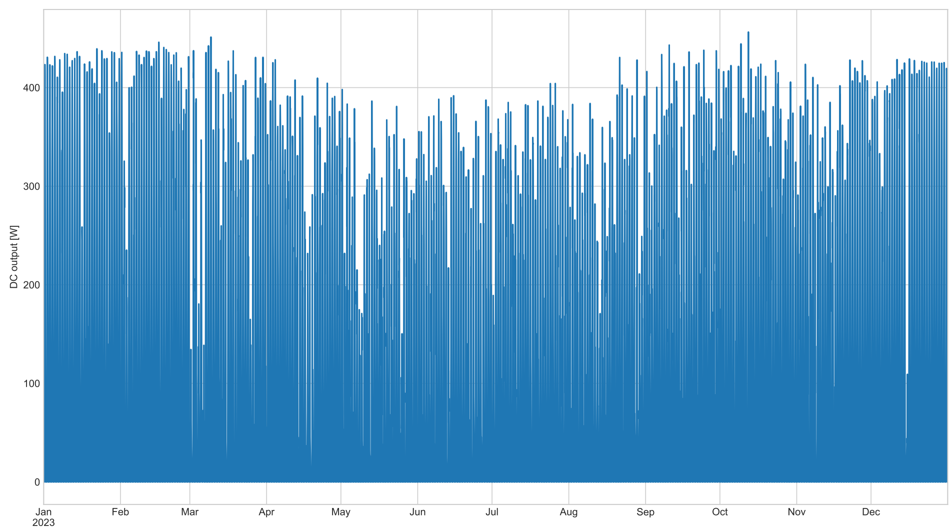
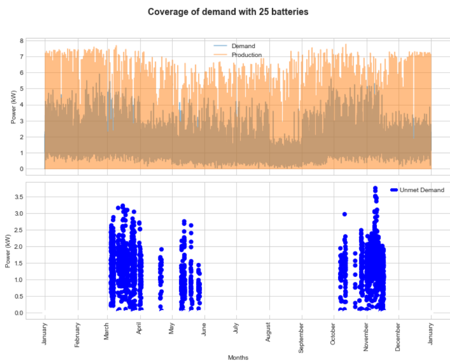
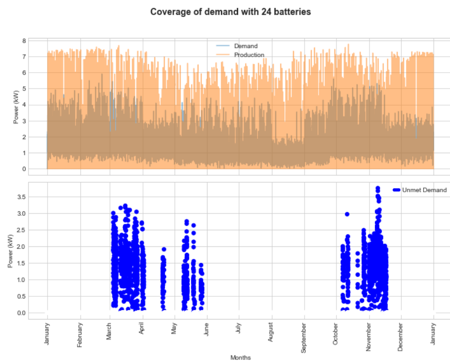


Figure I.2: Production profile from Zanzibar in Tanzania.

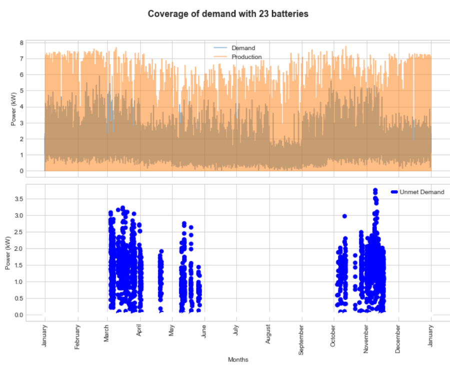
J Simulation Results from Example



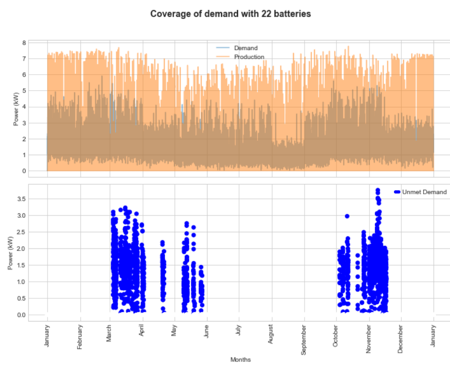
Number of PV panels needed: 17
Number of batteries needed: 25
Percentage of unmet demand: 4.237881588140877%



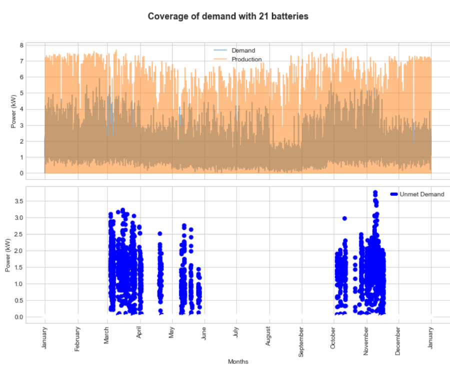
Number of PV panels needed: 17
Number of batteries needed: 24
Percentage of unmet demand: 4.317474902228061%



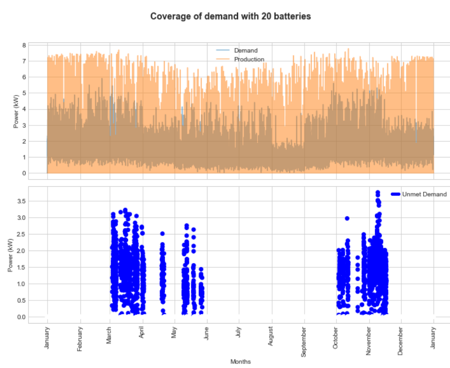
Number of PV panels needed: 17
Number of batteries needed: 23
Percentage of unmet demand: 4.39706821631524%



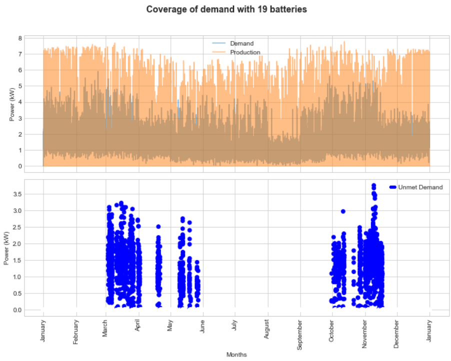
Number of PV panels needed: 17
Number of batteries needed: 22
Percentage of unmet demand: 4.476661530402423%



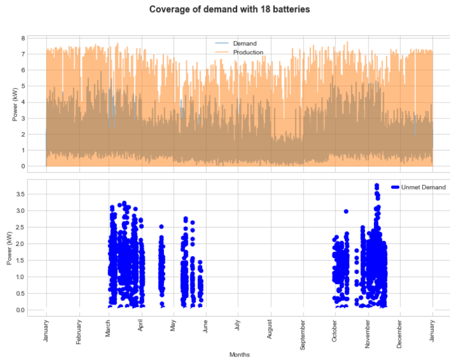
Number of PV panels needed: 17
Number of batteries needed: 21
Percentage of unmet demand: 4.556254844489607%



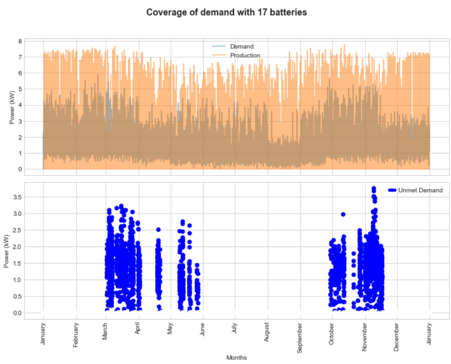
Number of PV panels needed: 17
Number of batteries needed: 20
Percentage of unmet demand: 4.635848158576785%



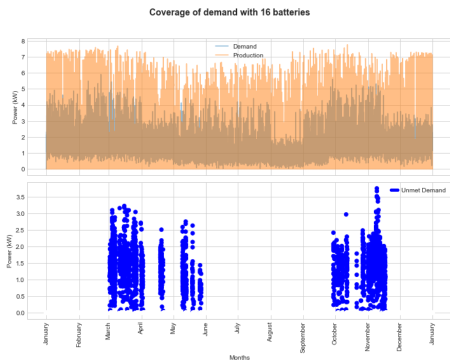
Number of PV panels needed: 17
Number of batteries needed: 19
Percentage of unmet demand: 4.7154414726639695%



Number of PV panels needed: 17
Number of batteries needed: 18
Percentage of unmet demand: 4.8092216177174265%

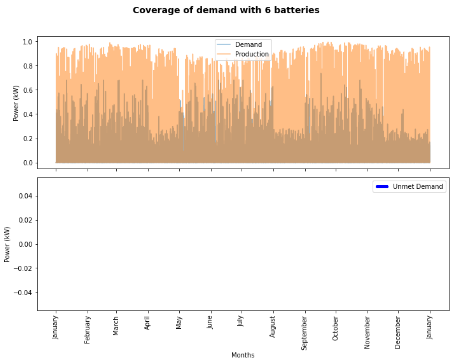


Number of PV panels needed: 17
Number of batteries needed: 17
Percentage of unmet demand: 4.915346036500337%

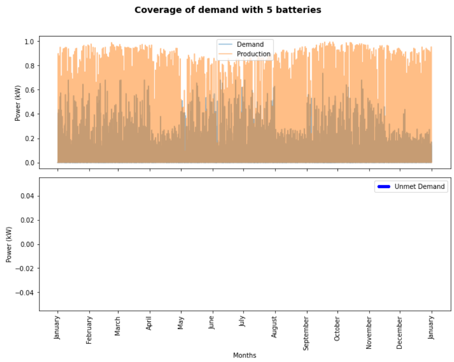


Number of PV panels needed: 17
Number of batteries needed: 16
Percentage of unmet demand: 5.021470455283251%

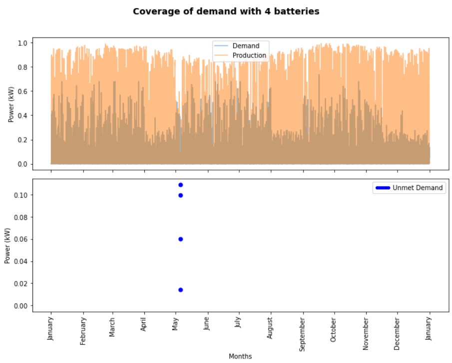
K Simulation Results Eco Moyo



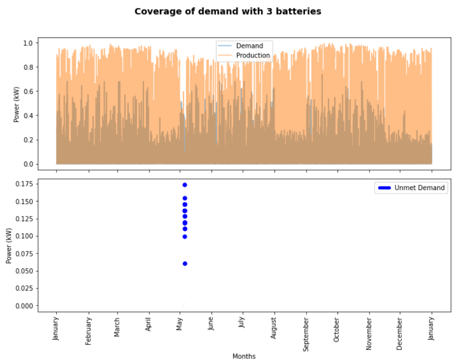
Number of PV panels needed: 1
Number of batteries needed: 6
Percentage of unmet demand: 0.0%



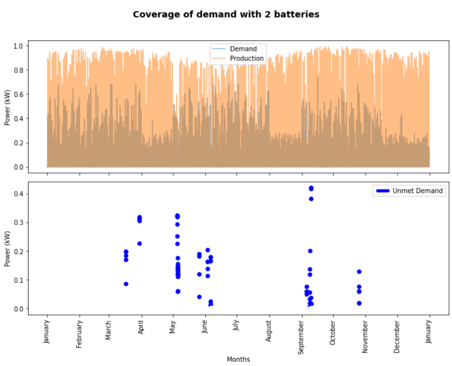
Number of PV panels needed: 1
Number of batteries needed: 5
Percentage of unmet demand: 0.0%



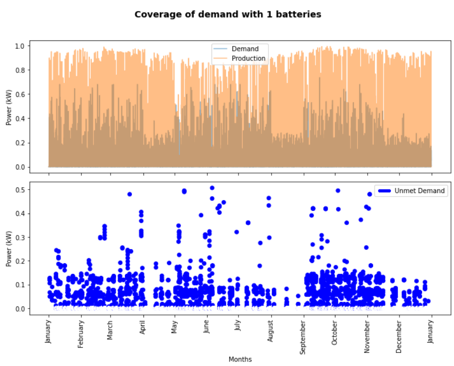
Number of PV panels needed: 1
Number of batteries needed: 4
Percentage of unmet demand: 0.0129205114474503555%



Number of PV panels needed: 1
Number of batteries needed: 3
Percentage of unmet demand: 0.11054562345133571%



Number of PV panels needed: 1
Number of batteries needed: 2
Percentage of unmet demand: 0.5318595683350392%



Number of PV panels needed: 1
Number of batteries needed: 1
Percentage of unmet demand: 7.014862471507914%

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