Department of Mechanical and Aerospace Engineering

Design & Optimisation of Off Grid Hybrid (Wind/PV) Power Systems for Rural Communities in Sub-Saharan Africa (SSA): A case for Zambia (Ndaiwala Village)

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Abstract

Access to electricity is vital in enhancing human well-being and driving economic growth. There is a continuous need to enhance energy efficiency and availability, making research in the energy industry very important. Recently, the energy industry has shifted its focus towards investing in clean and sustainable energy solutions to preserve the environment.

Energy access remains a major challenge in developing rural communities due to financial and geographical constraints. Notably, the Sub-Saharan Africa region faces the lowest electrification rates globally even though it possesses abundant renewable energy resources. To address this critical issue, this research develops a comprehensive methodology for designing and optimising off-grid hybrid energy systems specifically tailored to improve electricity access in rural communities that do not access to the central power system.

Prior research has explored off-grid power system designs to enhance electricity access in developing rural areas. This study aims to build upon existing approaches in the literature and improve the design methodology further. The study begins by developing a synthetic demand profile generator, which contrasts with the common estimation methods utilized by researchers. The novelty lies in incorporating behavioural switching characteristics associated with energy usage, thus offering more realistic demand profiles.

Additionally, the research addresses another crucial aspect often overlooked in existing design methodologies: energy demand forecasting. By incorporating this element, the proposed approach gains an advantage in creating more accurate and efficient off-grid hybrid energy systems.

Furthermore, the research explores optimization and sizing methodologies to enhance the reliability of the hybrid power system, further ensuring a stable and consistent electricity supply.

The research uses MATLAB software to implement the proposed methodology tools and subsequently applies it to a rural community in Zambia, showcasing its practicality and effectiveness. Ultimately, this research serves as a foundational methodology that can be adopted and improved upon to design autonomous off-grid hybrid energy systems.

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Nomenclature

Symbol	**Description**	**Units**
DC	Direct Current	A
PV	Photovoltaic	N/A
AC	Alternating Current	N/A
SSA	Sub-Saharan Africa	N/A
SDMs	Supply Demand Match Score	N/A
E_C	Energy Consumption	kWh
IRENA	International Renewable Energy Agency	N/A
SHS	Solar Home Systems	N/A
RESs	Renewable Energy Systems	N/A
LPSP	Loss of Power Supply Probability	N/A
P_{pv}	PV Power Output	N/A
PV	Photovoltaic	N/A
NOCT	Nominal Operating Cell Temperature	N/A
T_a	Ambient Temperature	℃
T_c	Cell Temperature	℃
B_t	Temperature coefficient	%/℃
G_i	Global Irradiance	kWh/m^2/day
NWT	Optimum Number of Wind Turbines	N/A
E_{Dem}	Energy Demand	kWh

1.0 Introduction

In this chapter, the research and study context are introduced. The section comprises subsections that emphasize the research objectives. The chapter commences with a broad background overview in section 1.1, followed by section 1.2 which delves into the problem statement and the author's motivation. Section 1.3 outlines the aims and objectives, while section 1.4 poses the research questions. The adopted methodology is explained in section 1.5, and section 1.6 gives the scope of this research. Lastly, section 1.7 provides an outline of the dissertation.

1.1 Background

The Sub-Saharan African (SSA) community faces a significant challenge in providing reliable energy to its population. The region has over 1 billion people yet has the lowest population with access to electricity of about 43%[1], [2]. Several factors contribute to these low energy access levels including political, social, and energy market structures. The geographical landscape of SSA communities contributes to the challenge of grid extension and the nature of rural communities that are scattered across clusters makes rural electrification through grid expansion a challenge[3]. The Sub-Saharan Africa region has potential for renewables like solar PV and wind power, yet the community remains to have the least share of the global energy mix[4].

Despite Zambia's potential for renewable resources like solar PV and wind energy in most parts of the country, it faces similar challenges as other countries in the Sub-Saharan community. The government has made efforts to improve energy access, but the country still struggles with low energy access, which currently stands at 40% of the population[5], [6]. In particular, the rural community has the lowest rate of energy access, with only 11% of the rural population having access to electricity, while 77% of the urban population has access[6].

Zambia has a significant potential for full decarbonisation of its energy mix, as hydroelectricity, which is clean and renewable, currently accounts for 85% of its energy generation[6]. However, the energy sector faces two main challenges. Firstly, the scale and reliability of the power system are affected by water levels in the bodies of water that power the grid. Secondly, there is a significant cost associated with extending the national grid to the remote and scattered rural population[5].

1.2 Problem Statement and Motivation

Off-grid and decentralized power systems offer the most viable solution for rural electrification but encounter several challenges[3]. These challenges include issues related to power supply reliability, such as under-sizing or oversizing of systems, as well as cost and power management challenges[7]. The lack of access to affordable electricity significantly contributes to the poor quality of life in rural communities. This energy poverty hinders economic growth and all the potential development associated with electricity access.

Optimising off-grid systems presents a challenge for power system developers, and it often begins with inefficiencies in demand estimation. The challenge revolves around accurately estimating the energy profile, taking into account user classification and behavioural patterns[8], [9]. The author aims to develop a methodology that facilitates the design and optimisation of off-grid power systems, promoting reliability and stability while keeping capital costs highly cost-effective.

1.2.1 Motivation

The author of this research is motivated to address the issue of energy poverty in rural communities, which often is significantly associated with distance from the power grid and lack of access to alternative electricity sources[2]. The author recognises that electricity access is a fundamental right and believes that urgent action is necessary to promote equality and improve the quality of life for rural communities through access to basic electricity. The objective of the research is to enhance the design process of off-grid power systems, aiming to provide affordable and reliable electricity access.

The transition from traditional fossil fuel-based energy sources to clean and renewable alternatives is crucial for promoting environmental well-being. Africa possesses abundant renewable energy resources such as hydro, solar, and biomass, which can contribute to clean energy generation. This research contributes to the integration of renewables into the energy mix and the mitigation of climate change.

The research takes into account the inherent variability of individual renewable energy sources and the associated challenges in power systems. This variability is particularly sensitive for off-grid power systems, as they do not have secondary energy sources to meet energy demands. To address this challenge, the author proposes a hybrid solution incorporating both solar PV and wind power into the system. By combining different renewable energy sources, the reliability of the power system is improved. The authors' motivation is to develop an autonomous power system capable of meeting the energy needs of rural communities at a low capital cost.

The author develops a stage-by-stage methodology to design and optimise off-grid hybrid power systems. This is an attempt to improve the reliability of rural power systems and improve the quality of life through access to clean and affordable electricity.

1.3 Aims and Objectives

The study aims to develop a methodology to design and optimise off-grid hybrid renewable power systems for rural communities and apply the methodology to a rural community in Zambia.

The intended outcomes of the study include:

- To develop an approach to design the energy demand profile generator.
- To introduce options to optimise the design of the energy demand profile generator.
- To investigate the renewable energy resource (Solar PV and Wind) availability in the selected location of applicability.
- To model the supply side of the energy system
- To carry out a sizing sensitivity analysis.
- To explore the energy source mix configurations and the impact on supply-demand matching score.
- To investigate the performance of the designed power systems in the different seasons experienced in the selected site of applicability.

1.4 Research Questions

Following the potential of renewables in the SSA region, the process of designing power systems to meet rural community needs to be efficient and cost-effective. The author attempts to optimise the design process of off-grid power systems for rural communities and consequently, this research is sought to answer the following questions:

1. What are the key factors that constitute a demand profile generator?

2. What’s the role of demographics in energy consumption?

3. What are the different energy supply modelling methods for Solar PV and wind energy?

4. What are the different methodologies that can be adapted for supply-demand matching?

5. What is the right energy source mix share ratio for the applicable selected location?

1.5 Adopted Approach

The author adopts an approach that attempts to improve the existing methodology in the design of off-grid power systems. Figure 1 gives a high-level methodology approach implemented in the study. Figure 2 shows a detailed design methodology for the study adopted by the author and the adopted methodology is achieved by the following selected steps:

Step 1: Review the literature on the design of off-grid power systems and note the limitations to improve the methodology.

Step 2: Develop an energy profile generator.

Step 3: Introduce optimisation options to improve the profile generator.

- Model behavioural patterns
- Capture user classes
- Introduce corrective factors.

Step 4: Establish a methodology for energy growth and forecast.

Step 5: Assess the energy resource in the location of applicability.

Step 6: Investigate the effect of system sizing sensitivity.

Step 7: Supply load matching analysis.

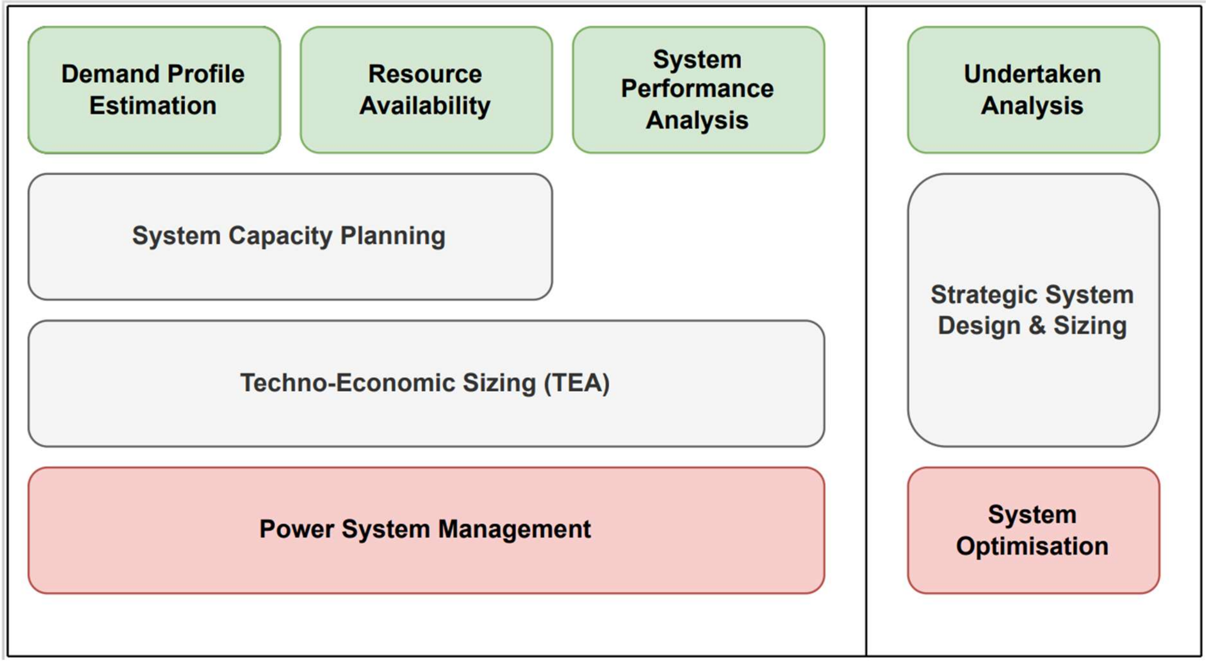

Figure 1: Overview Methodology flow

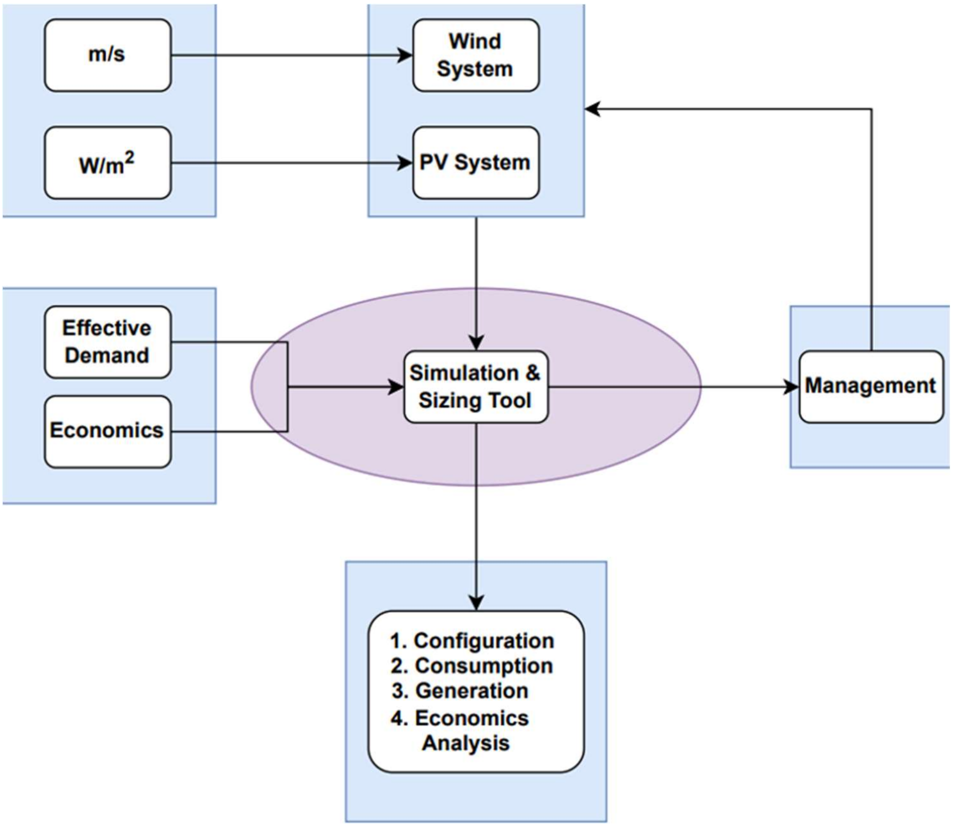

Figure 2: Detailed design methodology

1.6 Scope Statement

The research proposes an enhanced method for creating renewable off-grid systems suitable for use in Sub-Saharan Africa. The main objective of the study is to establish a framework for designing off-grid power systems that primarily address the improvement of demand estimation, sizing, and supply-demand matching. It is important to note that the study does not encompass secondary energy management possibilities such as storage or load shifting. However, it recognizes these options as potential areas for future exploration to develop a resilient and self-sufficient off-grid power system.

1.7 Thesis Outline

This dissertation has six chapters that explain the objectives and steps taken in the study by the author and are as follows:

Chapter One: In this chapter, the focus of this research is presented. The author provides an overview of the background and the reasons that drive their interest in the topic. Additionally, this chapter delves into the specific goals and purposes of the study.

Chapter Two: This chapter covers a literature review to understand the existing practice in off-grid power systems and establish an approach to improve the design methodology. The section covers the overall features of off-grid power systems. The section highlights the different configurations and the reliability of these power systems.

Chapter Three: The chapter explains the author’s methodology in designing and optimising off-grid power systems. The chapter outlines the approach used by the author to design and enhance off-grid power systems. It describes the systematic procedure employed to enhance the design of these systems, starting with the development of a methodology for estimating power demand and determining the system's capacity to meet this demand. Additionally, this section emphasizes the analysis conducted to determine the proportion of each energy source in the energy mix.

Chapter Four: In this chapter, the author showcases the applicability of the research methodology. The chapter presents a specific location chosen for its application and proceeds to develop estimations of power demand and sizing of the power system capacity for that location. An analysis of matching the demand and supply is also provided. The chapter attaches a case study to validate the study methodology developed in the research.

Chapter Five: This chapter provides a discussion and explains the limitations of the study. The section relates the methodology developed to the applied village. This chapter also highlights the advantages of the developed methodology and the author's reasons for adopting this type of methodology and gives the conclusion of the research highting key elements of this study.

2.0 Literature Review

This chapter, the literature review gives an overview of the UN sustainable development goals and the current sustainable energy access as the driving motivation for this research. The chapter also gives an overview of the off-grid systems, specifically examining the prevailing methods and developments in off-grid power systems. The review encompasses the fundamental aspects of off-grid systems, various configurations, the dependability of these systems, design methodologies, and the shortcomings associated with the current design approach.

2.1 Energy Sustainability Access

Creating global energy sustainability requires a close look at the current inefficiencies of the current energy system, technology, and energy policy. The world is striving to improve the energy crisis through sustainable development goals to overcome energy poverty[10]. Key indicators of energy poverty include low access to clean electricity and clean cooking facilities. This research is inspired to fight the existing energy crisis and promote the global energy sustainable development goals (SDG 7)[11]:

- Ensure universal access to affordable, reliable, and modern energy services.
- Substantially increase the share of renewable energy in the global energy mix
- Double the global rate of improvement in energy efficiency.

Over 700 million people globally do not have access to electricity and 670 million are projected to remain without electricity access to by 2030 with the Sub–Saharan Africa accounting for over 60% of this population. 84% of this world's population without access to electricity is in rural communities and about 2.4 billion people do not have access to clean cooking fuels and opt for other options like wood, kerosene, and diesel[10](see Figure 3).

The Sustainable development goals aim to improve the well-being of communities ensuring energy equality. Non-clean energy sources are responsible for premature death due to poor air quality, exposure to open fires, and inefficient cooking facilities globally accounting for over four million deaths every year[12][13].

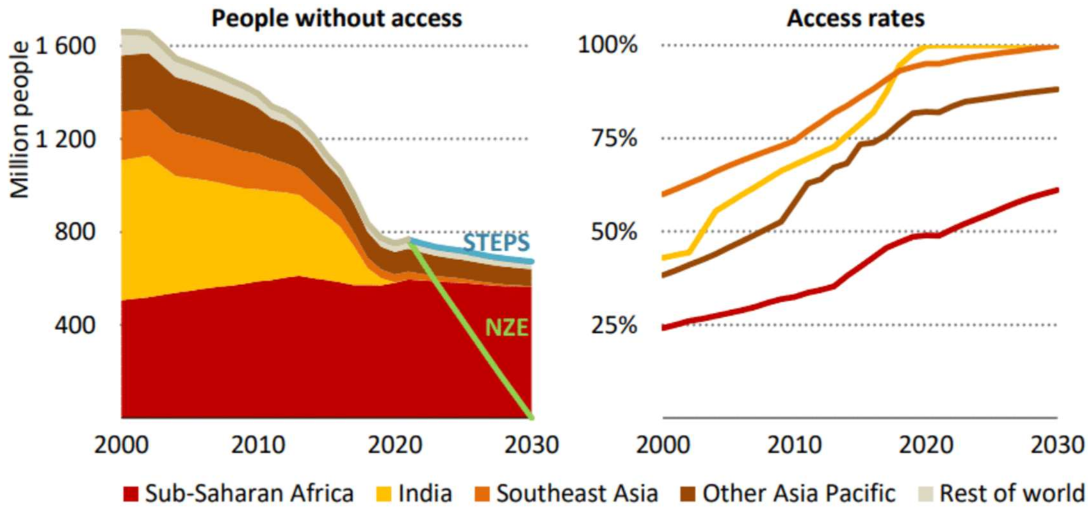

Figure 3: People without access to electricity and access rates to electricity by region (IEA. All rights reserved)

2.2 Off-grid Power Systems

The term off-grid system is agreeably defined as a system independent of a centrally connected power network. The need for an off-grid system ranges from the exorbitant cost associated with grid extension to the need for self-consumption and power reliability[14],[15]. The terminology refers to both mini-grids which usually serve larger loads and stand-alone systems which serve a single dedicated consumer. A closer look at the terminology arises a few questions regarding the type off-grid system in terms of the energy sources of the power system[16]. Figure 4 shows the different classes for off-grid power systems by application and Figure 5 shows the classification by the employed technology.

These energy systems have proven to be an economical option for rural electrification in preference to the traditional grid expansion[17] and provide beneficial uses like home uses, community service use, and production use applications to rural energy markets (agriculture, medicals, processing, etc)[17]–[20]. The biggest downside of these energy systems is the reliability of the power systems as it is observable that most systems experience failure sometime later after their commissioning. Design of robust systems is essential to ensure reliability and recent research and technology are highly focused on improving the life and dispatchability of off-grid power systems[21],[22][14].

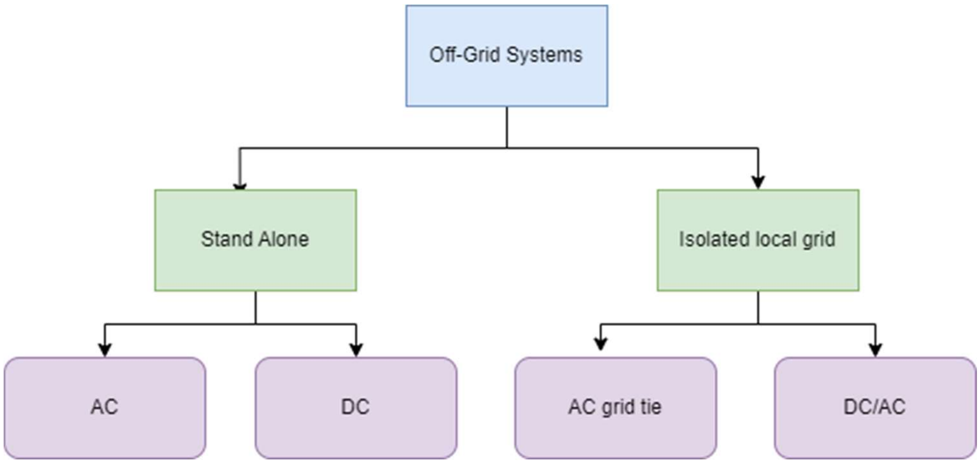

Figure 4: Categorisation of off-grid power systems

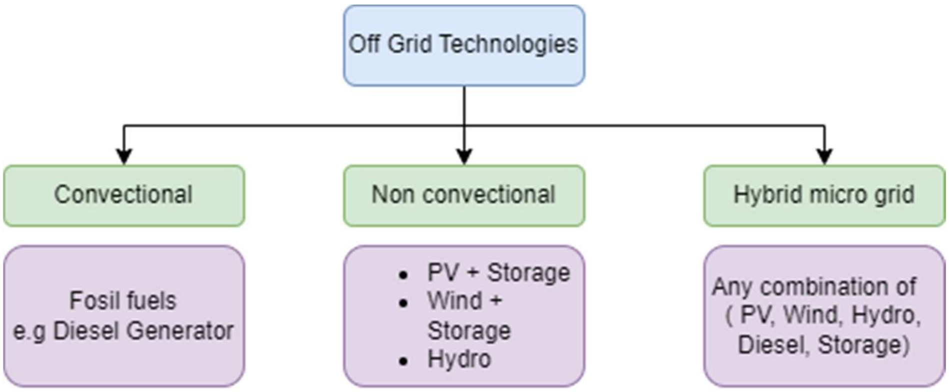

Figure 5: Off-grid technologies[23]

2.3 System Configurations

The significance of an off-grid power system lies in its ability to independently meet local energy requirements[24]. To accomplish this objective, the system incorporates components that perform similar functions to those of a conventional grid. Consequently, the system operates autonomously, providing power when needed to ensure stability and reliability. Since off-grid systems primarily rely on intermittent renewable energy sources, it becomes crucial to include additional measures such as energy storage and hybrid options to ensure a consistent energy supply[21], [22]. In technical terms, an off-grid power system comprises an energy source, control system, local transmission, and distribution network. The specific configuration of a system depends on its intended application and the processes it serves[14]. For example, if the system is designed to support daytime processes, incorporating storage may not be necessary, whereas it becomes essential for nighttime processes. Figure 6 shows possible renewable energy system configurations that can be employed to serve energy needs.

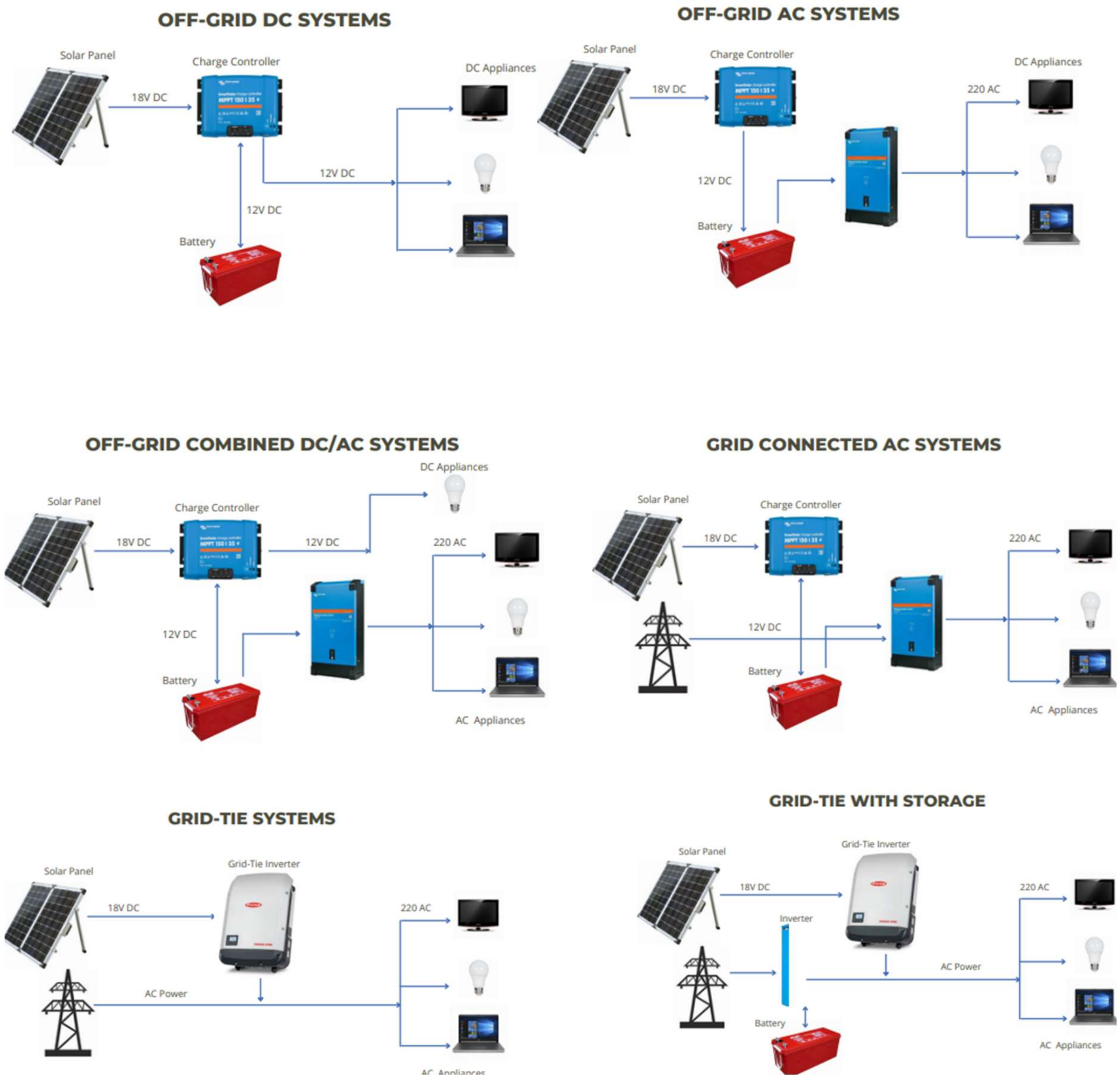

Figure 6: Different Renewable Power Systems Configurations[25].

2.3.1 Classification of off-grid power systems

The off-grid system matrix, as depicted in Table 1, classifies systems into two main categories: decentralized and distributed[23][26]. A decentralized system can cater to a single consumer, functioning as a standalone system. Alternatively, it can serve multiple consumers if configured as a microgrid system. However, it is important to note that decentralized systems rely on a single energy source. In contrast, a distributed system operates with multiple energy sources that feed into the system's distribution, resulting in a hybrid microgrid system. This configuration offers enhanced reliability and resilience due to the presence of multiple energy systems. By distinguishing between decentralized and distributed systems and highlighting their respective characteristics, the framework provides a comprehensive overview of the off-grid system landscape[20], [23].

Table 1: Off-grid system matrix[23]

<table>
<tr><th>Off-grid system matrix</th><th colspan="2">Decentralised</th><th>Distributed</th></tr>
<tr><td>Energy use</td><td>Stand Alone System</td><td>Micro grid system</td><td>Hybrid microgrid system</td></tr>
<tr><td>Household use</td><td>Home-based system</td><td rowspan="3">A system including a distribution grid</td><td rowspan="3">A system including a distribution grid</td></tr>
<tr><td>Community services</td><td>Community-based system</td></tr>
<tr><td>Productive uses</td><td>Production</td></tr>
<tr><td>Consumers number</td><td>One</td><td>Multiple</td><td>One or Many</td></tr>
<tr><td>Energy source</td><td colspan="2">One</td><td>Many</td></tr>
</table>

2.4 System Power Reliability

Power system reliability refers to the crucial aspect of a power network's ability to consistently match the electricity demand. It encompasses not only having sufficient capacity to meet the required demand but also ensuring the system remains operational without interruption[25], [27]. However, when it comes to renewable off-grid systems, inherent challenges arise due to the intermittent nature of renewable energy sources. This unreliability stems from their dependence on weather conditions, such as sunlight for solar photovoltaic systems and wind for wind energy. The extent of this unreliability varies depending on the geographical location of the power system[14], [16].

To ensure stability in these energy systems, the dominant solution for mitigating the effects of low-generation periods is energy storage, despite the associated costs. Another effective approach to address the intermittence of renewables is the development of hybrid power systems that can complement the energy supply during different periods. In the design process, conducting a thorough analysis of the extent of energy loss of the systems becomes crucial for making informed decisions[28][26].

2.5 Existing Off-Grid Design Approach

The design and planning of a power system commence by calculating the energy demand, which is essential for determining the appropriate system capacity. This calculation involves aligning the demand with the available energy resources to ensure a sufficient supply capable of meeting the evaluated energy demand[24], [29]. Once the demand is established, subsequent design steps focus on enhancing efficiency and optimization, tailoring them to the specific requirements of the project at hand.

In the existing literature, the design process often relies on average parameters such as wind speeds and solar irradiance, as well as estimates of energy consumption[30]–[32]. However, to further improve the current design process, the author introduces additional aspects that are not commonly incorporated, including:

- Consumer Behavioural Consumption: By considering consumer behaviour and patterns of energy usage, the design process can be refined to reflect the actual consumption habits of the target users. This approach provides a more realistic representation of energy demands and allows for better sizing and optimization of the power system.

- Demand Diversity Factors: Incorporating diversity factors accounts for the variations in energy usage patterns among different consumers or sectors. This factor takes into consideration the actual likelihood of simultaneous peak demand occurrences and assists in sizing the system to handle peak loads efficiently, resulting in improved system reliability.

- Energy Forecast and Demand Growth: Anticipating future energy demands is crucial for designing a power system that can accommodate future growth and expansion. By incorporating energy forecast models and considering demand growth projections, the design process becomes proactive and enables the system to be scalable and adaptable to changing needs.

- Supply-Demand Match (Reliability) Analysis: A comprehensive analysis of supply and demand dynamics ensures an optimal match between energy generation and consumption. By considering factors such as energy storage capacity, renewable energy intermittency, and demand response mechanisms, the design process can effectively balance supply and demand, minimising wastage and maximising system efficiency.

2.5.1 Review on appropriate sizing optimisation

The literature proposes various approaches for sizing off-grid systems, as illustrated in Figure 7 [33], [34]. While these approaches differ in the parameters used to estimate demand and determine the required power capacity, they all share a common objective:

to match the estimated demand with the available energy resources. Key objectives in the design process, as outlined in the literature [27], [34], [35] include:

- Minimise Cost: The design process aims to minimise both capital costs (initial investment) and maintenance costs associated with the off-grid system. By considering cost-effective components and system configurations, the overall expenses can be reduced.

- Minimise System Capacity: Efficient system design involves minimising the required capacity while still meeting the energy demand. This helps optimise the system's performance, reduce resource requirements, and improve cost-effectiveness.

- Maximise Generation: The design process strives to maximise the generation of energy from available resources. By considering factors such as solar irradiance or wind speed, the system can be optimised to capture and utilise the maximum energy potential.

- Minimize Loss of Power Supply Probability (LPSP): System reliability assessment is an important aspect of the design process. By minimizing the probability of power supply loss, the system can ensure a consistent and reliable energy supply to meet the demand. This involves considering factors such as backup systems, energy storage, and contingency plans.

One commonly used approach is the probabilistic method, which involves utilising annual average energy resources, such as wind speed or irradiance. Additionally, an option within this method is to account for the most unfavourable period, ensuring that the system can still meet the demand during low resource availability conditions.

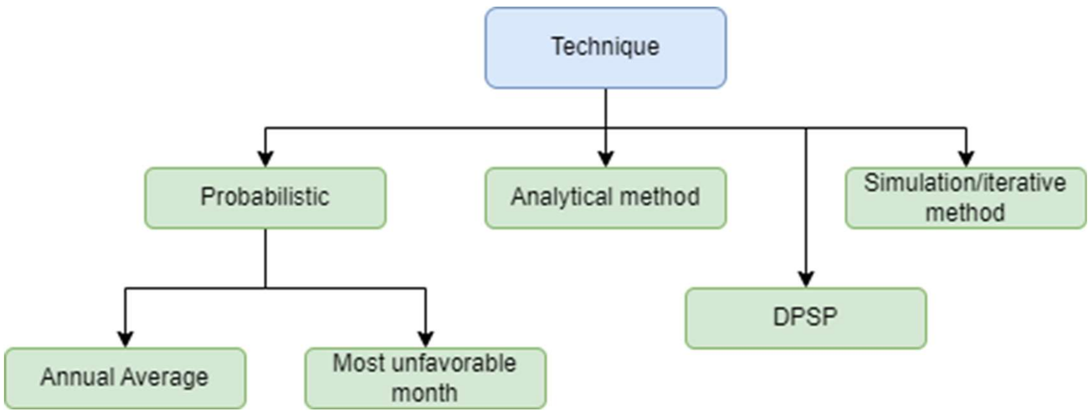

Figure 7: Sizing approaches in the literature

3.0 Adopted Study Methodological Approach

This chapter presents the methodology employed by the author for the study, focusing on the design and optimisation of off-grid systems for rural communities. The objective of the research is to enhance existing methodologies in the literature and enhance the robustness of the design process. The chapter is divided into two sections, each detailing the adopted approach for a specific aspect of the design process.

The first section of the chapter elaborates on the methodology adopted to estimate an effective energy demand that is more realistic and representative of energy consumption habits. This approach goes beyond traditional methods by considering consumer behaviour and consumption patterns.

The second section covers the methodology adopted for determining the system capacity size. This aspect is crucial for ensuring the off-grid system can adequately supply the estimated demand. The methodology employed in this research goes beyond simplistic approaches and takes into account various factors such as energy resource availability and system reliability. By incorporating these elements, the system capacity size can be optimized to strike a balance between meeting the demand efficiently and minimizing costs and system capacity.

Overall, this chapter introduces an improved methodology for the design and optimization of off-grid systems, aiming to enhance the robustness and effectiveness of the design process. By considering realistic consumption habits and adopting a comprehensive approach to determine system capacity size, the research contributes to the development of more accurate, reliable, and cost-effective off-grid systems.

3.1 Demand Estimation

Estimating the energy requirements of a community or application is a crucial step in designing off-grid systems, considering the limited availability of resources and the challenge of reliability due to intermittent energy sources. The energy needs encompass various applications, including electricity for lighting, and appliances, as well as thermal applications such as heating and cooling[15], [19], [27].

In many underdeveloped countries, rural electrification is still insufficient, and traditional options like biomass from wood and LPG remain the predominant sources for cooking and heating. However, it is important to address the limitations and drawbacks associated with these traditional options, such as environmental concerns, health risks, and dependence on finite resources.

The study proposes a demand estimation methodology, which is depicted in Figure 8 below. The author aims to introduce a novel approach to developing a tool that can effectively generate a synthetic energy demand profile.

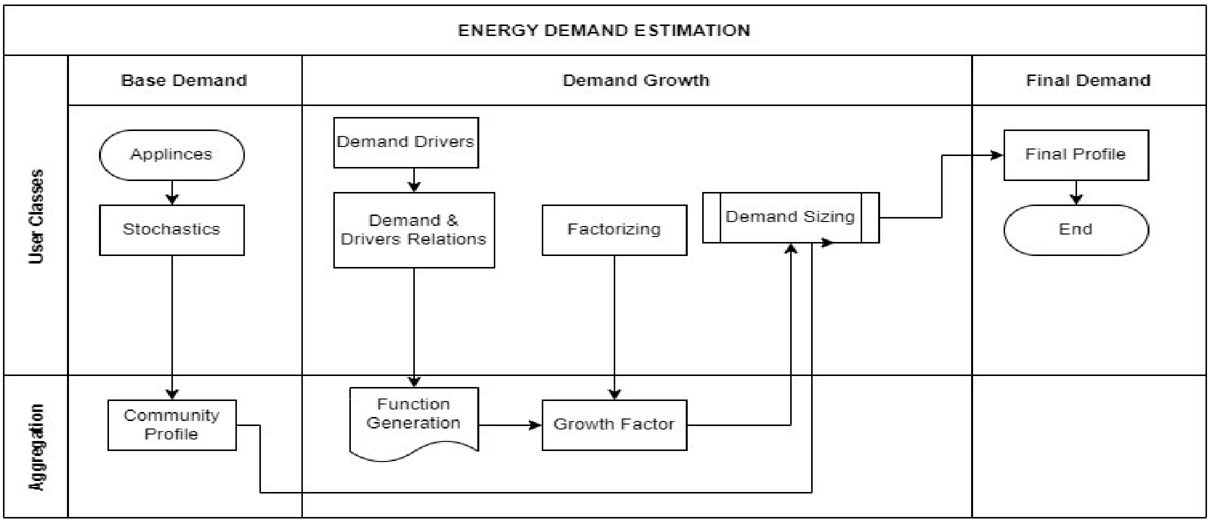

Figure 8: Demand estimation methodology

3.1.1 Selected Approach

Following an extensive review of existing methods utilized in establishing energy demand profiles [8], [9], [36], [37], the research embraces a bottom-up methodology with an approach similar to an approach adopted by Mandelli [32]. The chosen approach aims to capture various features associated with energy consumption, including appliance switching, randomness, and other pertinent attributes. The methodology encompasses the following key characteristics [9],[33],[34]:

- Energy user classification
- Demand aggregation
- Appliance ownership and consumption rating
- Stochastic switching of appliances and diversity factors
- Switching window periods and the likelihood of switching appliances within such window periods.

The adopted model is carefully crafted to fulfill the essential requirements of energy consumption for communities, incorporating several key features. These features include:

Demand diversity factor: This aspect is crucial to prevent overestimating the system capacity. Ideally, the peak demand of the system would occur if all appliances were switched on simultaneously[38]. However, in reality, the switching on and off of appliances is influenced by various factors[23]. The model takes into account this characteristic, specifically addressing it for larger power systems.

Load sensitivity/Critical and non-critical loads: The model incorporates the concept of load sensitivity, specifically distinguishing between critical and non-critical loads. It empowers the user to allocate the sensitivity of each load based on the likelihood of appliance usage. This is achieved by introducing window periods specific to each appliance type, along with probabilities or likelihoods of the appliances being switched on or off within those defined periods[23], [26].

Aggregation: The model is specifically designed to capture the effective demand from diverse users connected to the network. It facilitates the aggregation of individual demand profiles to accurately represent the total energy consumption.

3.1.2 Mathematical Modelling of the Adopted Approach

Energy consumption (Ec) is mathematically expressed as a function of power rating over time, as denoted by equation (1). The primary goal of the modelling process is to precisely capture the complex characteristics associated with these parameters, focusing on identifying the factors that influence cumulative power consumption and its variation throughout the day. This introduces the concept of power aggregation and switching, which the model comprehensively incorporates through equation (2). Additionally, the model defines a function in equation (3) that precisely characterizes the switching behavior and probability of appliance use[23], [39]–[41].

$$E_C(t) = P \times t \tag{1}$$

$$E_C = \sum_{j=1}^{N} N_j * \left[\left(\sum_{i=1}^{n} n_{ij} * p_{ij} * f(h_{ij})\right)\right] \tag{2}$$

$$f(h_{ij}) = R_{ij} * h_{ij} \tag{3}$$

The terms in the equations are defined as follows:

E_C: Energy consumption

N_j: Number of users/classes

n_{ij}: Number of appliances

p_{ij}: Appliance power rating

$f(h_{ij})$: Switching function.

h_{ij}: Hour of use

3.1.2.1 Model implementation

A MATLAB code is developed to model the profile generator see Appendix II. This MATLAB script allows the user to input information about the number of users, number of appliances, power rating, and usage windows for each appliance, Figure 9 provides a visual representation of the adopted methodology. The script generates profiles for each user's appliances based on the controlled switching of appliances within the specified usage windows. The script then calculates the hourly consumption for each user and the total hourly consumption for all users.

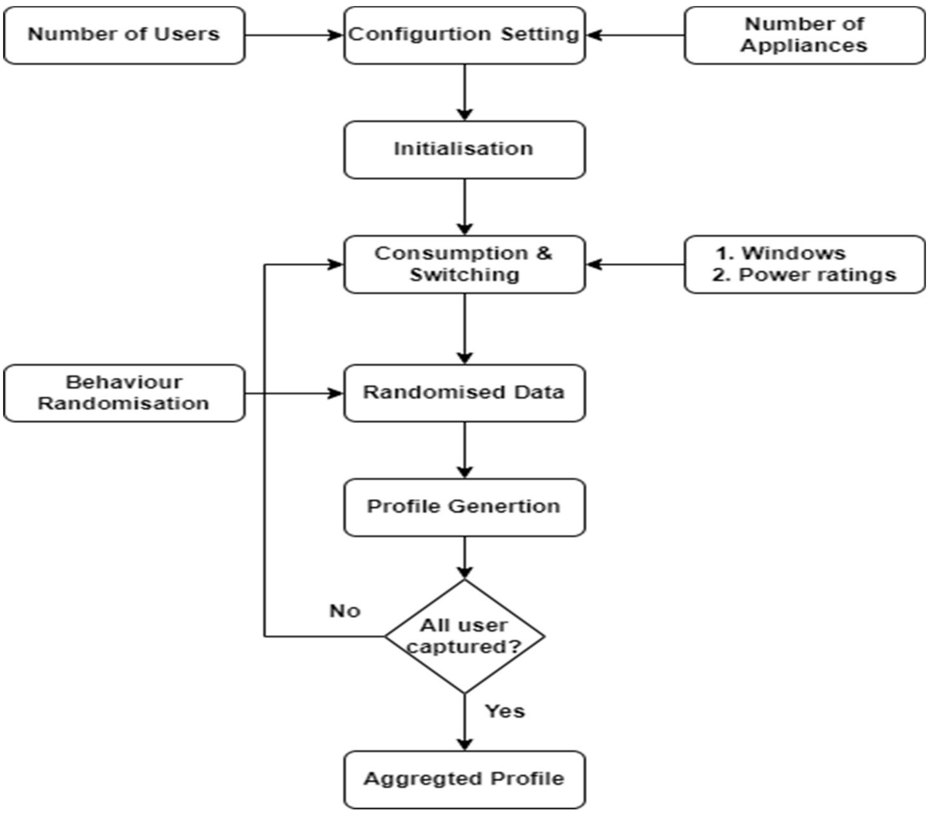

Figure 9: MATLAB code design approach

The features of the code:

- Prompts the users to enter the number of class users and the number of appliances.

- Arrays are initialized to store the profiles for each user and the hourly consumption.
- The user is prompted to input the power rating and windows for each appliance using a loop.
- For each appliance, the user is prompted to input the start index, end index, and percentage of ones or on states for each window using another loop.
- The script loops over each user and generates appliance profiles based on the randomly generated on/off states within the specified windows and bias.
- The generated profiles are multiplied by the appliance power rating and stored in the array called userProfiles.
- The script calculates the hourly consumption for each user by summing the profiles.
- The total hourly consumption for all users is calculated by summing the userHourlyConsumption array.
- The script exports the hourly consumption data for each user and the aggregated hourly consumption to a CSV file named "combined_hourly_consumption.csv".

In summary, this code allows users to input information about appliances, their power ratings, and usage windows. It generates demand profiles for each user's appliances within the specified windows and calculates the hourly consumption for each user. The data is then exported to a CSV file, and the hourly consumption is displayed for each user.

Figures 10-13 show the profiles generated by the demand profile tool developed by the author. The tool demonstrates the effect of behaviour on appliance switching and diversity factor. The demand profile of the community is an aggregation of both community and house loads.

Table 2: Illustration of the designed profile generator

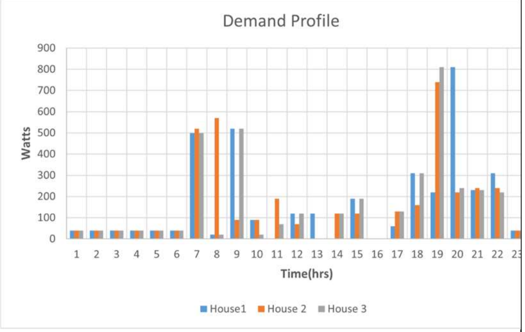

Figure 10: Demand profile for three houses

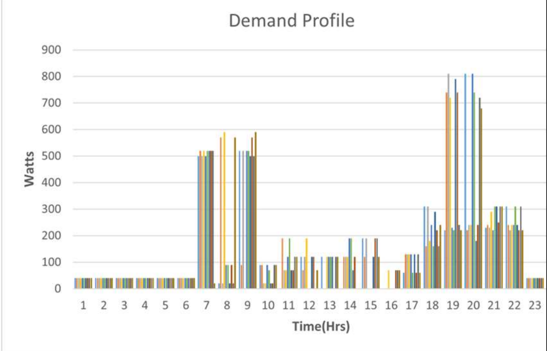

Figure 11: Demand profile for ten houses

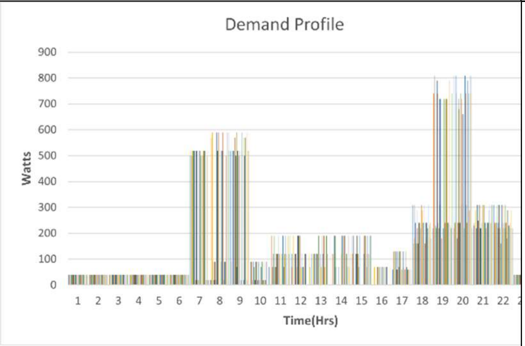

Figure 12: Demand profile for thirty houses

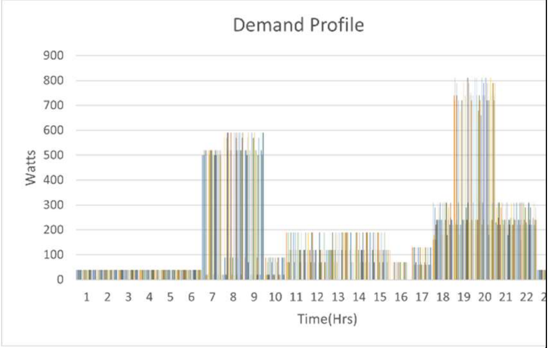

Figure 13: Demand profile for fifty houses

3.1.3 Demand Optimisation Options

One of the significant challenges associated with off-grid systems is the occurrence of system failures post-commissioning. As the population and economy grow, energy consumption inevitably increases, placing additional strain on isolated grids[42], [43]. This escalating demand poses a risk of exceeding the system's capacity, potentially leading to blackouts.

The author incorporates an approach that includes estimating the effective demand by introducing corrective factors[44]. Additionally, the author integrates energy demand forecast growth to enable the design of systems capable of meeting future energy needs without the risk of failure[45].

3.1.3.1 Corrective Factors

Generation of a representative demand profile is king to ensuring the stability of power systems and ensuring this correction procedure may be applicable depending on the nature of the data used during the demand estimation process. Some key factors adopted in the Sizing Handbook[44] by the GIZ ProSolar include:

- Current demand factor (C_1`)
- Commercial value factor(C_2`)
- Data collection factor (C_3`)

The effective factor (C_F`) is derived by multiplying all the corrective factors. The current demand factor takes into consideration the demand that the power system being designed will not be able to meet, whether due to insufficient capacity or a portion of energy to be met by an alternative energy source. The commercial factor is utilized to ensure the project's economic viability and reflects the community's willingness to pay for electricity as not every community member may be able to afford the electricity cost. The data collection factor acknowledges that the data collection process may not cover the entire population in the community hence to get the total demand this factor is employed[44], [46]. These factors are then applied appropriately to modify the demand profile, ensuring it meets the energy requirements of the community.

$$C_1 = 1 - \frac{\text{Energy to be covered by alternative sources}}{\text{Maximum Demand}} \tag{4}$$

$$C_2 = \frac{\text{Available cash to be collected}}{\text{Capital Cost}} \tag{5}$$

$$C_3 = \frac{\text{Total Users}}{\text{Sample size in the survey}} \tag{6}$$

$$C_F = C_1 * C_2 * C_3 \tag{7}$$

These correction factors are applicable based on the specific situation and the survey method employed, considering the available data. The primary objective is to develop an effective demand profile that aligns with the site’s requirements and to optimize the profile to ensure economic viability[34], [47].

3.1.3.2 Demand Growth Forecast

Developing a model to forecast energy demand requires understanding the relationship between various parameters that impact energy consumption. The best approach involves training the model using historical data to uncover patterns, correlations, and dependencies among these parameters[48].

Key parameters to consider when developing a demand forecasting model include population growth, economic indicators (such as GDP, industrial output, and employment rates, etc.), energy efficiency improvements, technological advancements, energy pricing, weather patterns, and policy changes[43], [49], [50].

Advanced models, tools, and techniques like regression analysis can be employed to develop accurate and robust demand forecasting models. These models can capture complex relationships, account for seasonality and trends, and incorporate exogenous variables that influence energy demand[51], [52].

Continuous validation and refinement of the model using real-time data are essential to ensure its accuracy and reliability. Regular updates to the model with new data will improve its forecasting capabilities and enable stakeholders to make informed decisions regarding energy infrastructure development, resource allocation, and policy planning.

This study involves the development of a MATLAB code (provided in Appendix III) to analyse energy data as the dependent variable and other key parameters (control variables) that exhibit significant correlations with energy consumption. The dataset is divided into training and test sets to establish the relationship between the dependent and independent variables, as illustrated in the diagram depicted in Figure 14.

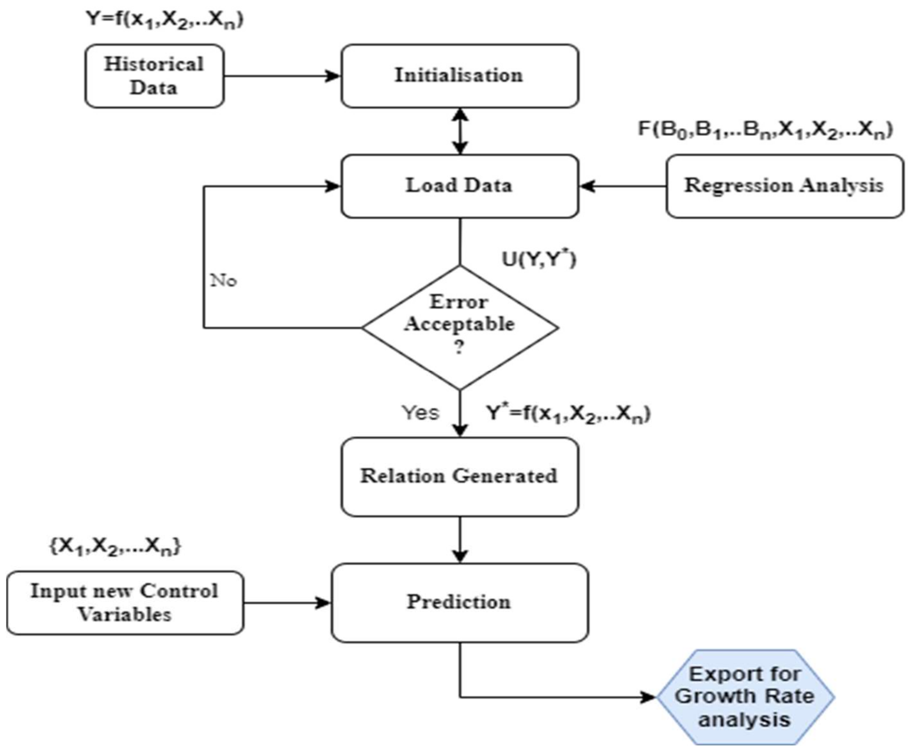

Figure 14: Demand growth forecast methodology

The MATLAB code features:

1. The user is prompted to enter the name of an Excel file containing initial data (including the file extension). This file should have both the dependent variable and the control variables.
2. A prompt to enter the column index of the dependent variable in the Excel file.
3. A prompt to enter the column indices of the control variables in the Excel file. Multiple column indices can be provided as a list.
4. The script reads the data from the initial Excel file using **xlsread** and extracts the dependent variable and control variables based on the provided column indices.
5. The script enters a loop that allows the user to choose the order (degree) of the polynomial regression model they want to try. To exit the loop, the user can enter 0.
6. Inside the loop, the script checks if the sizes of the dependent variable and control variables match (i.e., they have the same number of rows). If not, it raises an error.
7. The script performs polynomial regression with the chosen degree on the control variables, creating a design matrix **X** that includes the powers of the control variables up to the selected degree.
8. The polynomial regression coefficients are calculated using the backslash operator \.
9. The script calculates the accuracy score (R-squared) for the initial regression model by comparing the predicted values with the actual dependent variable values.
10. The user is asked whether they want to proceed with the trained model. If they choose to continue (**'Y'** or **'y'**), the **initialOrder** variable is updated to store the degree of the polynomial regression model that was selected.
11. If the user decides not to proceed with any trained model (by entering 0 or choosing **'N'**), the script exits.

12. If the user decides to proceed with the trained model, they are prompted to provide another Excel file containing new control variables (including the file extension).

13. The new control variables are read from the new Excel file, and their column indices are obtained from the user.

14. The script checks if the number of new control variables matches the number of control variables in the model. If not, it raises an error.

15. The script performs prediction on the new control variables using the trained model (with the selected degree) and displays the predicted values.

16. The script ends after displaying the predicted values or if the user chooses not to proceed with any trained model.

The objective is to define the expectation function($\mathrm{E(Y|X)}$) for the dependent variable (Y) the consumption given values of control variables (X) as in the following equations:

$$\mathrm{Y(x_i) = B_0 + B_1X_i + \cdots B_nX_i} \tag{8}$$

$$\mathrm{E(Y|x) = Y_i - U_i} \tag{9}$$

$$\mathrm{\widehat{Y}_i = \widehat{B}_0 + \widehat{B}_1X_1 + \cdots + \widehat{B}_nX_i} \tag{10}$$

$$\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{U_i} = \sum_{\mathrm{i=1}}^{\mathrm{n}} \left(\mathrm{Y_i - \widehat{Y}_i}\right) \approx 0 \tag{11}$$

Where the symbols represent the following:

i. $\mathrm{Y(x_i)}$: Dependant variable

ii. $\mathrm{E(Y|x)}$: Expectation or population regression function

iii. $\mathrm{\widehat{Y}_i}$: Estimator based on a sample since not everything is observable about the data

iv. $(\mathrm{\widehat{B}_0, \widehat{B}_1, \widehat{B}_n})$: Regression coefficients

3.2 Power System Capacity Design

The power system's capacity is contingent upon the scale of energy demand it needs to meet. Renewable energy systems face a challenge due to their intermittent nature which makes sizing power systems challenging. This complexity is exacerbated by the variable energy consumption resulting from the stochastic behavior of energy usage. For instance, seasonal changes significantly impact energy consumption. In winter, there is a higher demand for thermal loads for heating, while during summer, cooling appliances become critical loads. The dynamic nature of these loads makes it challenging to achieve an optimally sized system that can effectively meet the fluctuating energy requirements[53]–[55]. The basic approach to improving system reliability when sizing with renewables is the use of more than one energy source in the energy mix to form a hybrid renewable system.

In the literature, several approaches to system capacity sizing are commonly classified as either software-based or traditional methods, as depicted in Figure 15. The primary objective of these approaches is to minimise costs, system size, and supply shortages, and simultaneously maximise energy generation[56]–[58].

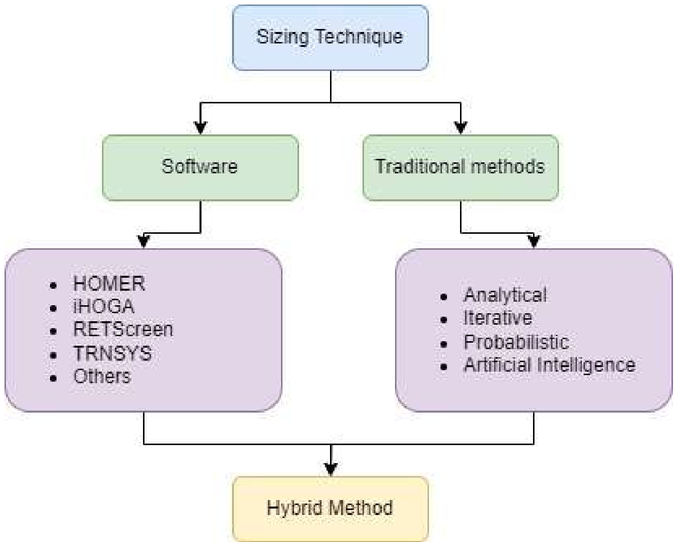

Figure 15: Sizing Techniques

3.2.1 Adopted Approach

The author employs a hybrid approach, combining traditional methods to enhance and optimize the design[57], [59], [60]. The sizing methodology proposed by the author commences with a probabilistic appraisal and an analysis of the capacity's impact. This analysis involves inputting various parameters corresponding to different seasonal experiences, such as the wet rainy season, cool dry season, and hot dry season. Figure 16 illustrates the employed methodology by the author, which utilizes an iteration method to select an optimal configuration for the hybrid system. The objective function within the design parameters aims to simultaneously minimize power loss and maximize power generation as an optimization technique[30], [53], [54]. This analysis is applied to the various seasons experienced at the site, and a performance analysis is conducted to assess the reliability of the designed power system.

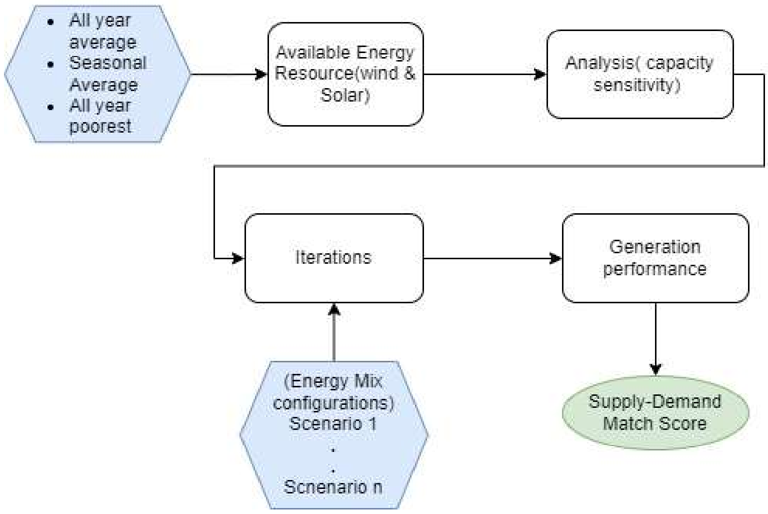

Figure 16: Adopted Sizing methodology.

The system configuration adopted is depicted in Figure 17. Various energy source mix ratios are simulated to assess the generation performance, and the configuration with the highest supply-demand match score is identified as the most reliable system, chosen for implementation.

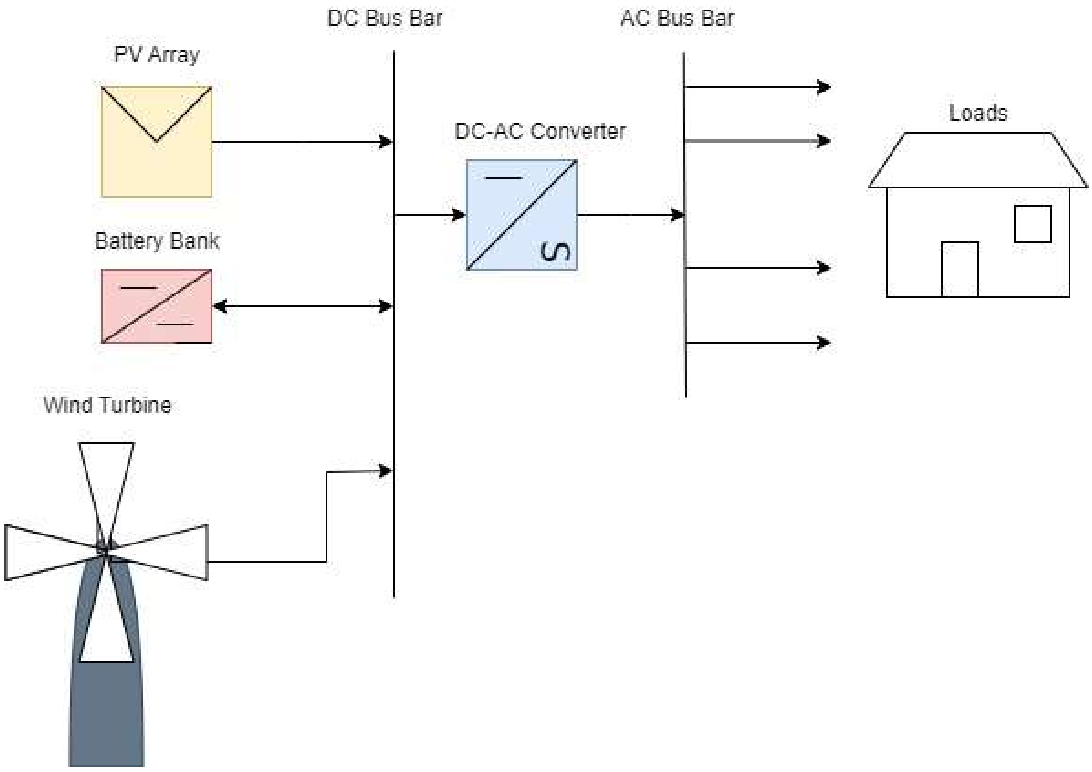

Figure 17: Power system configuration

3.2.2 Mathematical Modelling of the Adopted Approach

The modelling methodology begins my calculation of the effective area (A_E) as defined in equation (12). this parameter affects the energy production for both solar and wind systems:

1. Effective area for solar systems refers to the plant land area for putting the PV modules.
2. Effective area for wind systems refers to the swept area of the turbine.

The primary objective is minimising the system cost and capacity size as in equation (12) and equation (13). The total energy production over the 12 months to meet the energy demand is calculated using equation (15).

$$f(C)_{min} = C_c + C_m \tag{12}$$

$$\Delta P_{min} = P_{Gen} - P_{Dem}; P_{Gen} > P_{Dem} \tag{13}$$

$$A_{E,i} = \frac{\sum_i^{12} E_{Dem,i}}{\sum_i^{12} E_{Gen,i}} \tag{14}$$

$$E_{GenTotal} = E_{Load} = \sum_{i=1}^{12} E_{Gen,i} * A_{E,i} * \delta_{eff} \tag{15}$$

These basic equations form the basic model for the capacity of the hybrid system where these symbols represent the following:

C_c: Capital cost, C_m: Maintenance cost, P_{Gen}: Generated power per unit area(**m²**),P_{Dem}: Power demand, $A_{E,i}$: Effective area, δ_{eff}: Efficiency factor

3.2.2.1 Solar PV Generator Modelling

The author employs a sizing methodology akin to the one found in existing literature, which assesses the surface area needed to harness the irradiance effectively and meet the energy requirements[61][57], [62], [63]. This methodology is illustrated in the schematic presented in Figure 18 and has been accomplished through the creation of a MATLAB code (refer to Appendix III). The sizing process considers crucial parameters associated with the utilized PV technology, such as efficiency, derating factor, and the impact of temperature on the available irradiance. These considerations enable the determination of the precise area and quantity of PV modules required to fulfil the energy demands effectively.

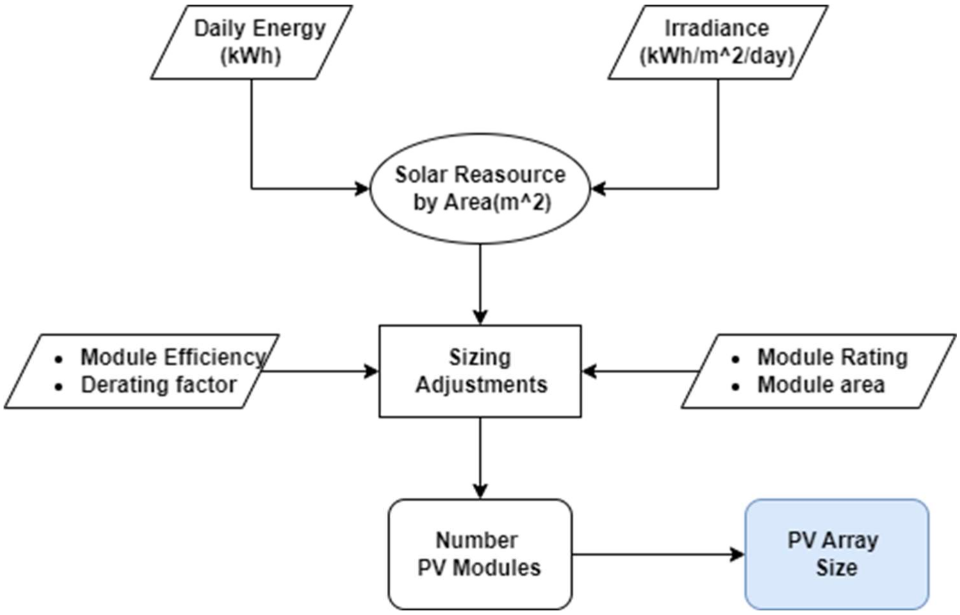

Figure 18: PV sizing methodology

The performance of the PV module depends on the specific technology used and varies based on the manufacturer[57]. The proposed model takes this critical factor into account while sizing the system, providing the user with the flexibility to choose essential parameters such as PV reference efficiency (η_r), temperature coefficient (β_t), PV module area (A_m) and the Nominal Operating Cell Temperature (NOCT). There are several other factors the designer needs to consider when sizing PV systems that result in the efficiencies in the system like wiring losses, overheating and loose connections which may depend on the temperature too. An appropriate sizing factor needs to be considered when designing the capacity of the power system.

The power output of the PV array (P_{PV}) can be estimated according to equation (16) with the parameter (η_g) resenting the overall efficiency (defined in equation (18)), G_i represent the global irradiance ($\mathbf{W/m^2}$) and the N represents the number of PV modules on the plant's effective area A_{PV} in $\mathbf{m^2}$. T_c and T_a are temperature parameters with Tc representing the cell temperature and Ta the ambient temperature.

$$\mathrm{A}_{PV} = \mathrm{N} * A_m \tag{16}$$

$$\mathrm{P_{PV}} = \eta_g * A_{PV} * \mathrm{G_i} \tag{17}$$

$$\eta_g = \eta_r * \eta_{pt}[1 - \beta_t(\mathrm{T_c} - \mathrm{T_{cref}})] \tag{18}$$

$$\mathrm{T_c} = \mathrm{T_a} + \left(\frac{\mathrm{NOCT} - 20}{800}\right) * \mathrm{G_i} \tag{19}$$

3.2.2.2 Wind Energy Generator Modelling

The adopted methodology is similar to that used for modelling the solar PV generator, in which the author assesses the effective swept area (A) of the wind turbine (WT) that is necessary to meet the energy demand [59], [64]. Figure 19 depicts the methodology that was chosen. Equation (20) evaluates the site's average wind speed for a sample size of n, and equation (21) evaluates the probability of a specific wind speed.

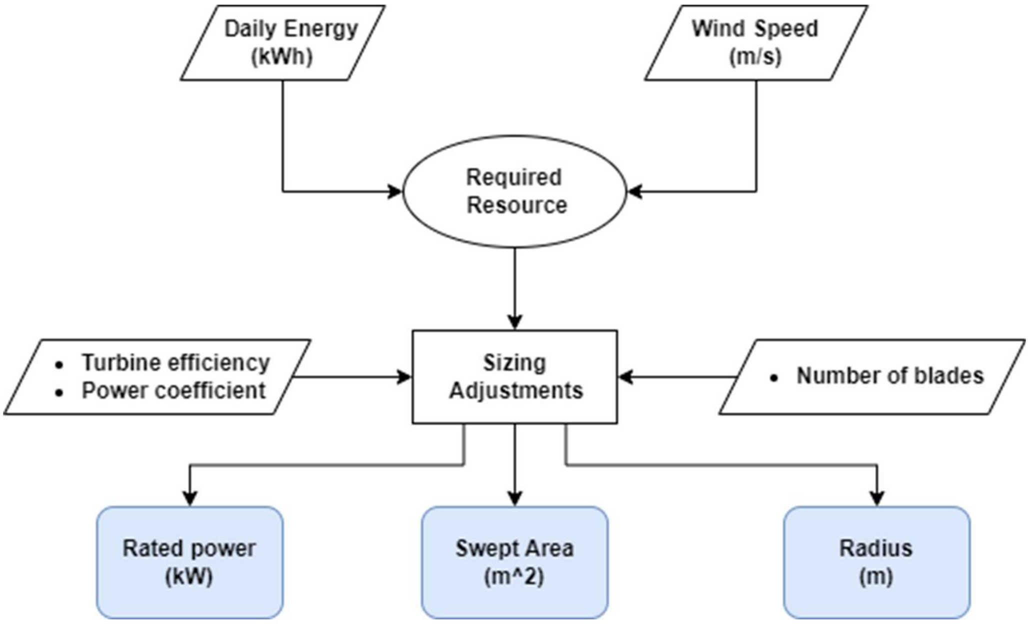

Figure 19: Wind sizing methodology

Compared to solar irradiance, wind power is less predictable, but it has a longer generation time during the day. The amount of energy produced depends on both the wind's speed (μ_i) and the height (h) of the wind turbine (WT). The losses in the mechanical system and the generator side, which are described as efficiency factors η_m and η_g, respectively, are the other elements impacting the performance of turbines[65][64], [66]. The symbol for the overall efficiency factor is η_o. To scale up production the number of WTs can be increased to an optimum number of wind turbines (NWT) to meet the energy requirement. Based on the literature and features of wind energy the power produced from the WT is calculated as equation (22) but the turbine operation is sensitive to the available wind speed at the turbine blades, the most appropriate estimation of the power generated by the WT is by the equation (25) [65]. Table 3 shows the description of all the symbols used in the equations.

$$\bar{\mu} = \frac{1}{n}\sum_{i=1}^{n} \mu_i \tag{20}$$

$$P(\mu_i) = \frac{m_i}{n} \tag{21}$$

$$P_w(t) = \frac{1}{2}[\rho * A * \mu^3 * \text{NWT} * \eta_o] \tag{22}$$

$$\eta_o = \eta_m * \eta_g * c_p \tag{23}$$

$$\mu(h) = \mu(hg) * \frac{h}{hg}^{\alpha} \tag{24}$$

$$P_w(\mu_i) = \begin{cases} 0\ ;\ \mu_i > \mu_F\ , \mu_i < \mu_c \\ P_R;\ \mu_i \geq \mu_R \\ \hline P_R * \dfrac{\mu_i - \mu_c}{\mu_R - \mu_c}; \mu_c \leq \mu_i \leq \mu_R \end{cases} \tag{25}$$

$$P_{w,avg} = P_R * C_F \tag{26}$$

Table 3: Symbols

Symbol	**Description**
$\bar{\mu}$	Average wind speed
$P(\mu_i)$	Probability of a particular wind speed
m_i	Number of observations
μ_F	Cut out wind speed
μ_c	Cut in wind speed
C_F	Capacity factor
P_R	Rated power
ρ	Air density
c_p	Power coefficient

3.2.3 Power System Reliability

The research strives to enhance power system reliability by integrating two energy sources into the energy mix: solar and wind. This combination aims to complement each other's power generation and improve the overall stability of the system. To assess the system's reliability, the study conducts an analysis of power losses during various seasons on the site, alongside a load matching analysis. Moreover, an energy configuration analysis is performed to identify the most favourable option that minimises power losses while maximising the supply-load match score[28], [34], [54], [67].

The Loss of power probability ($\mathrm{LPSP(t)}$) is evaluated to determine periods when supply falls short to meet the energy demand ($\mathrm{E_{Dem}}$) as in equation (27) and the loss of power of supply ($\mathrm{LSP(t)}$) is determined using equation (28) throughout the year. The supply-demand match score ($\mathrm{SDMs(t)}$) is determined as in equation (29) and such that $\mathrm{SDMs(t)} \geq 1$indcates that the demand meets the demand and vice versa implies the supply is not sufficient to meet the energy requirements. To improve supply matching in hybrid systems storage is a primary approach, but this study does not explore any storage options and battery storage ($\mathrm{E_{Bat}(t)}$) analysis is the potential avenue in future design. $\mathrm{E_{PV}(t)}$ and $\mathrm{E_{Wt}(t)}$ represent the energy generated from the PV generator and the energy generated from the wind turbine generator respectively[33], [35].

$$\mathrm{LPSP(t)} = \frac{\sum_{t=1}^{T=8760} \mathrm{LSP\ (t)}}{\sum_{t=1}^{T} \mathrm{E_{Dem}(t)}} \tag{27}$$

$$\mathrm{LSP(t)} = \mathrm{E_{Dem}(t)} - \mathrm{E_{PV}(t)} - \mathrm{E_{Wt}(t)} - \mathrm{E_{Bat}(t)} \tag{28}$$

$$\mathrm{SDMs(t)} = \frac{\sum_{t=1}^{T=8760} \mathrm{E_T(t)}}{\sum_{t=1}^{T=8760} \mathrm{E_{Dem}(t)}} \tag{29}$$

$$\mathrm{E_T(t)} = \mathrm{E_{PV}(t)} + \mathrm{E_{Wt}(t)} + \mathrm{E_{Bat}(t)} \tag{30}$$

Secondary energy sources are key in stabilising supply, preferably storage plays a key role by allowing energy shifting to meet demand at all times. The energy supply side is made dynamic by the nature of storage, the storage option depends on the specific power system and the loads that are met for example in terms of cooling loads it could be ideal to provide cooling beyond the required temperatures to allow the cooling even during moments when there is no supply and as such thermal storage help stabilise the system.

4.0 Applicability of the Study Methodology: A Case for Zambia

This chapter highlights the applicability of the proposed study methodology in the design of off-grid hybrid systems powered by solar PV and wind energy. The chapter gives a brief description of the applicable site location and the applicable results from the proposed design methodology for the energy community. In section 4.1 a concise overview of the selected community for the applicability of the study is presented, section 4.2 provides an in-depth assessment conducted to evaluate the available resources at the selected site as well as the current energy demand of the community, section 4.3 focuses on a detailed analysis of system's capacity sensitivity to different sizing configurations and section 4.4 highlights the impact on the system's performance resulting from various energy mix configurations.

4.1 Selected Site

Zambia experiences a tropical climate with a high potential for solar energy generation. The climate experienced in Zambia is between the wet and rainy seasons and cool and dry seasons. Ndaiwala is a village in the eastern remote part of Zambia with coordinates of 12° 47' 56" south and 32° 56' 2" east. The community has a population size of about 6023 with about 234 households and like several other rural communities in Zambia, it has no access to the national grid. The community has three community schools with one health centre. The population is on the increase hence the need for electricity access to meet the economic needs and for use in public facilities like shops, the police post, schools, and the health centre.

4.2 Energy Demand and Resource Availability

Available energy resource in the selected community is assessed and evaluated. Both solar irradiance and wind resource are found significant to support a hybrid power systems design[68], [69]. The community energy assessment is shown in Appendix I and the energy profile is generated using the designed profile generator. The energy profile is mapped against the available energy resource to analyse the supply match during the seasons experienced in Zambia.

4.2.1 Demand Profile

The predominant energy demand in Ndaiwala primarily caters to lighting, basic household appliances such as televisions, and essential public facilities like shops, schools, and health centres. Presently, thermal energy needs for cooking and cooling are not a primary necessity, and the community continues to rely on traditional methods like open fires for heating and utilises firewood or LPG for cooking purposes[70], [71].

Using the proposed generator, the community energy profile is generated based on the community energy use behaviour. Figure 20 shows the community public facilities by class and Figure 21 shows an aggregation of the public facilities.

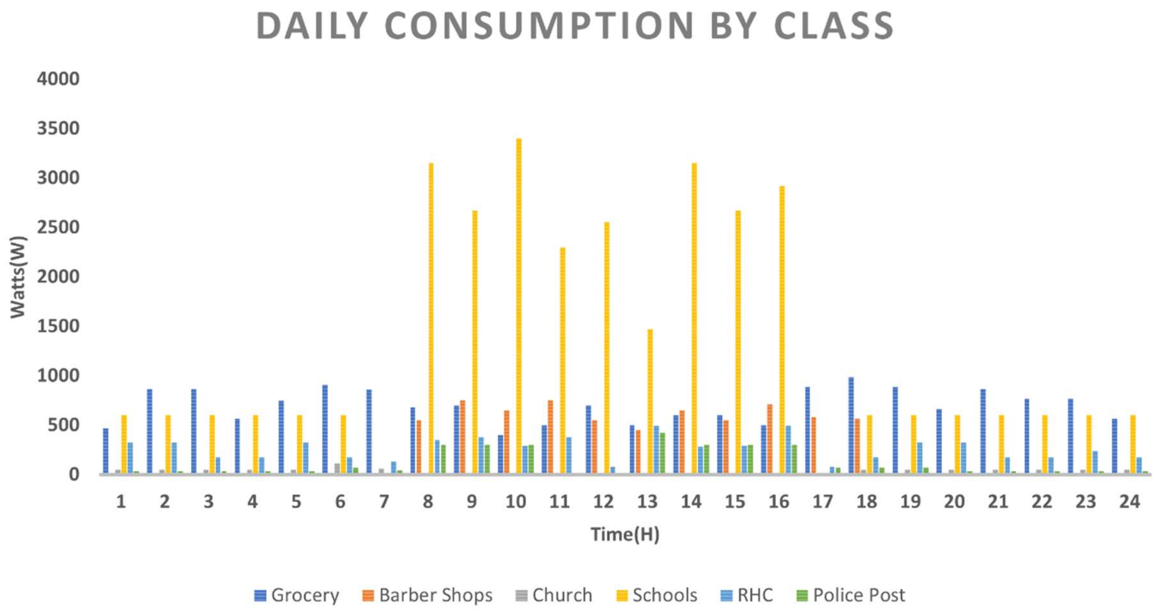

Figure 20: Community public facilities energy profiles

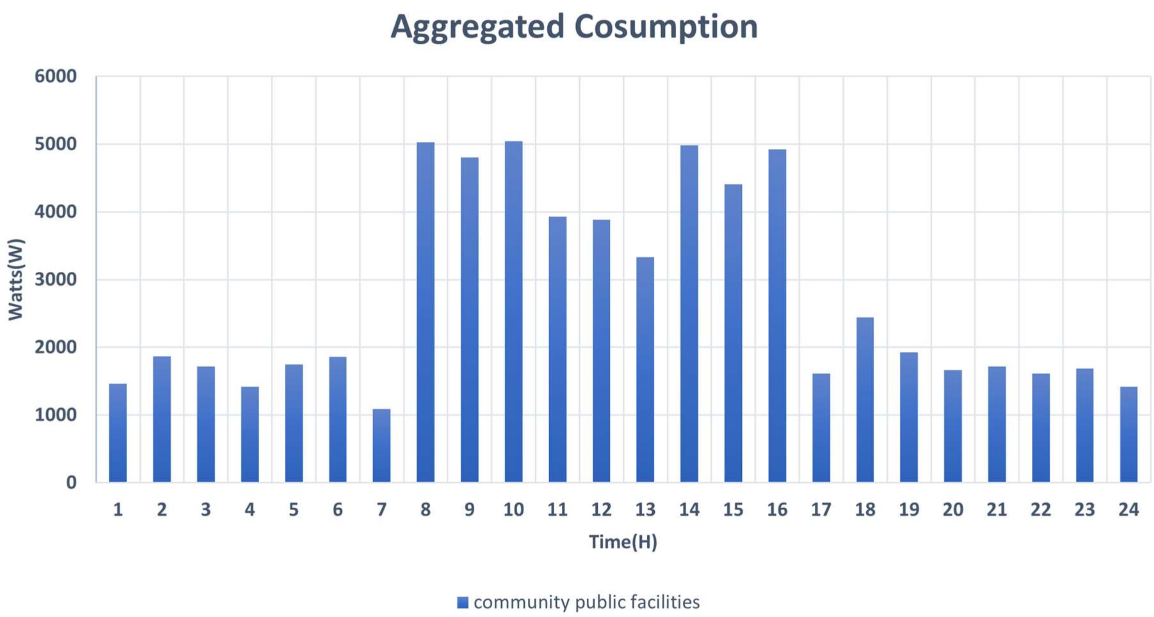

Figure 21: Aggregated community public facilities

The tool demonstrates its capability to generate the behavioural pattern of the community energy consumption and it is visible that the operation of most appliances of public facilities occurs during the day. While the household profile may exhibit a slight variation, the tool effectively showcases this difference for the community, as depicted in Figure 22 with higher consumption during the evening hours as this is the period when people are back in their homes.

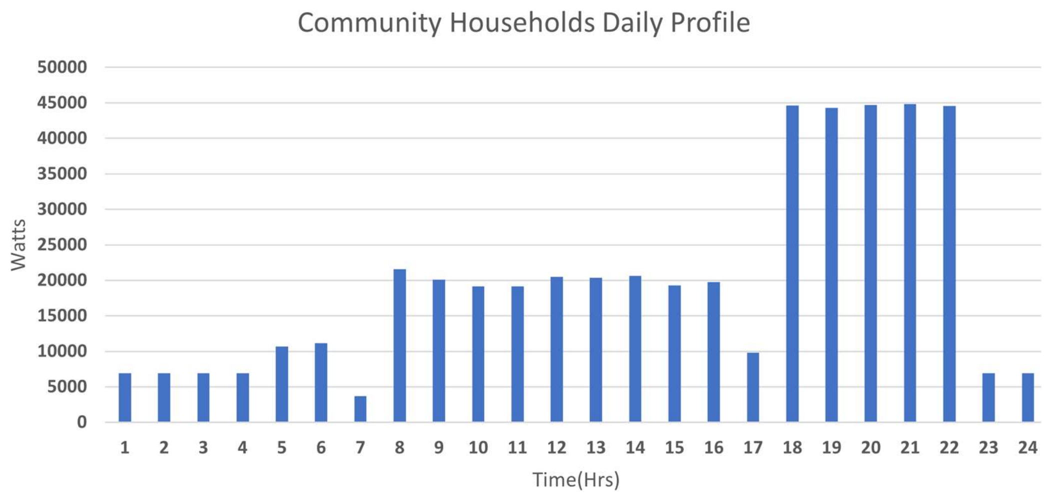

Figure 22: community household profile

The total community profile is the aggregation of the public facilities and the community households as shown in Figure 23. The generated profile is sensitive to the switching behaviour of the appliances and based on the specific application and users, the developed tool produces a profile specific to the energy usage pattern.

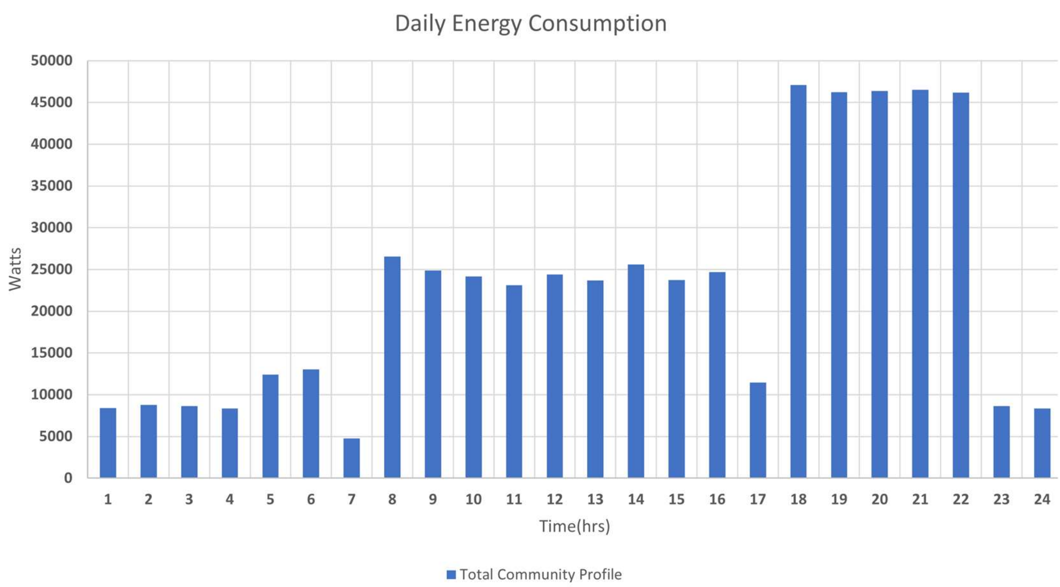

Figure 23: Total community energy profile

4.2.2 Solar Resource

Zambia experiences an annual average of approximately 3000 hours of sunlight, with an average irradiance of 5.5 kWh/m2/day, indicating a substantial and favourable solar energy resource. The selected site benefits significantly from this solar resource, as evident from the available resource as shown in Figure 24 [68], [69], [72].

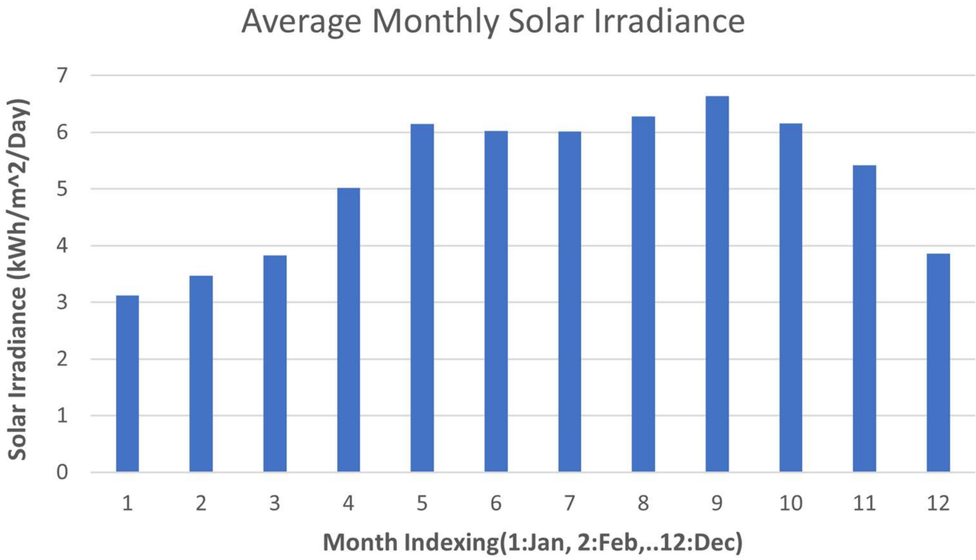

Figure 24:Average monthly irradiance in Ndaiwala

When examining the daily average irradiance received on-site, it is noticed that the lowest irradiance occurs between December and February, with values as low as 2.5kW/m2/day, as illustrated in Figure 25. The evidence indicates that a power system solely reliant on solar PV is not reliable due to the unstable availability and variation of solar resources on site.

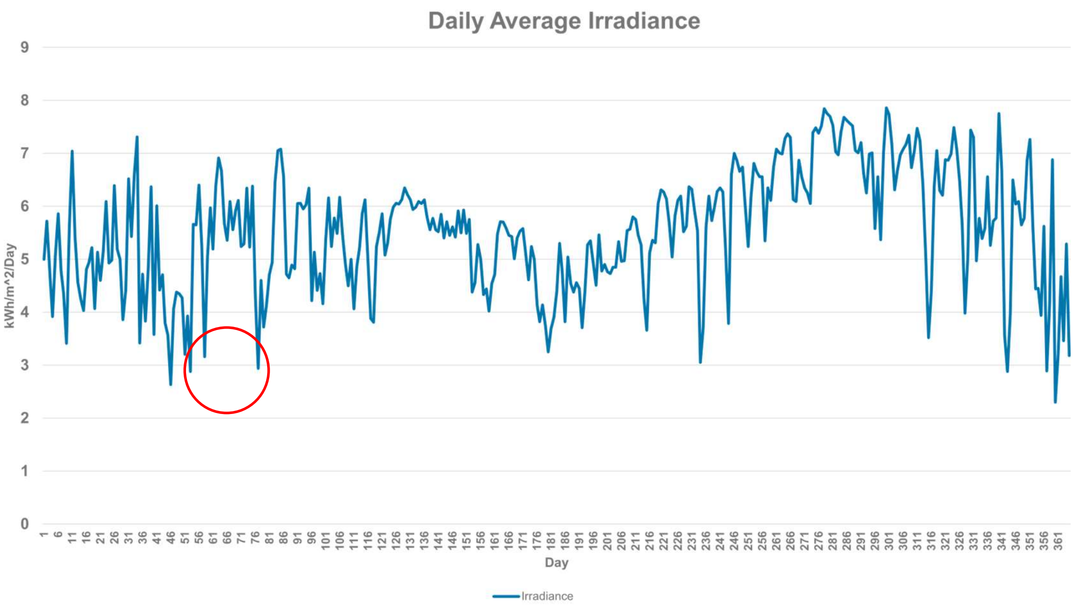

Figure 25: Daily average irradiance in Ndaiwala

4.2.3 Wind Resource

The eastern province of Zambia receives the highest wind resource following its higher elevation. Figure 26 shows the wind speeds at 10m and 50m height with the highest average speeds in the months between September and October. [69], [73]

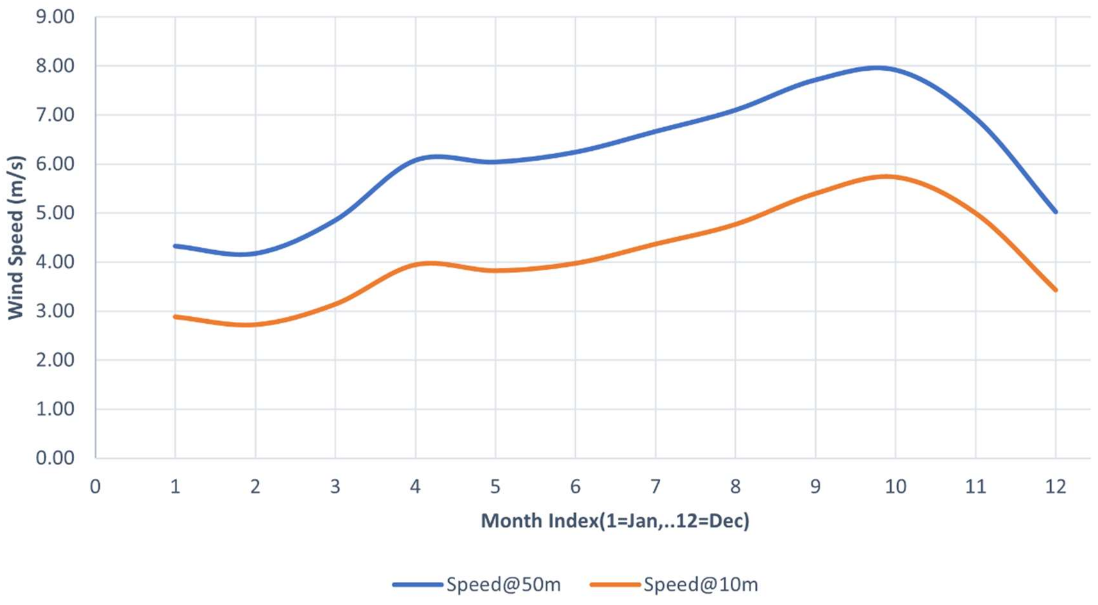

Figure 26: Average monthly wind speeds

The site undergoes substantial variations in wind speeds, leading to a highly unstable power supply. The wind speed fluctuates between values as low as below 2m/s and as high as 8m/s, presenting a notably unstable energy resource. However, it is worth noting that despite this variability, there are more hours of wind resources availability compared to the solar resource.

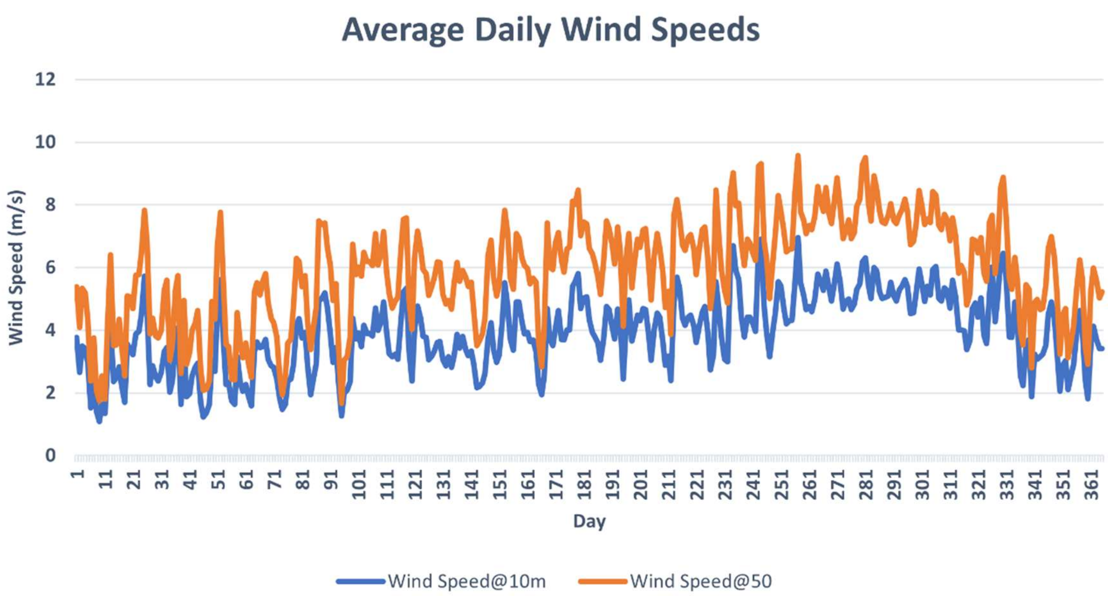

Figure 27: Average daily wind speeds in Ndaiwala

4.3 Sizing and Sensitivity

A sensitivity analysis is done to analyse the effect on the system capacity size and resource availability in the design. Three parameters are considered to analyse the sensitivity namely:

- All-year average resource
- All-year minimum resource
- Poorest month's average resource

The power system's capacity is influenced by the available resources during the design process, and this sensitivity is evident in the three selected parameters. The first design parameter is determined by considering the all-year average resource on-site having solar irradiance of 5.5kWh/m^2/day and a wind speed of 4.1 m/s at 30 meters height. The second design parameter is based on the all-year minimum resource, leading to a solar irradiance of 2.3kWh/m^2/day and a wind speed of 1.8 m/s at the height of 30 meters. Finally, the last design parameter is based on the poorest month's average, with an irradiance of 3.1 kWh/m^2/day and a wind speed of 2.83 m/s at 30 meters height.

Table 4 illustrates how these design parameters impact the system capacity, showcasing the sensitivity of the design process.

Table 4: Sizing sensitivity to available energy resource

Solar PV Generator Sizing		
All-year average resource (Case I)	**All-year minimum average resource (Case II)**	**Poorest month average resource (Case III)**
148*530Wp (78.4kW PV)	354*530Wp (188kW PV)	263*530Wp (140kW PV)
Wind Generator Sizing		
All-year average resource (Case I)	**All-year minimum average resource (Case II)**	**Poorest month average resource (Case III)**
6*10kW (60kW Wind Farm)	22*10kW (220kW Wind Farm)	8*10kW9*(80kW Wind Farm)

The PV generation capacity is analysed for January, considering the system's three cases mentioned above. January represents the month with the lowest solar resource; hence the system performance is investigated for this month and the results are depicted in Figure 28. On the other hand, the three cases for the wind farm are examined for February, which is characterized by the lowest wind speeds. The results for these wind farm scenarios are shown in Figure 29.

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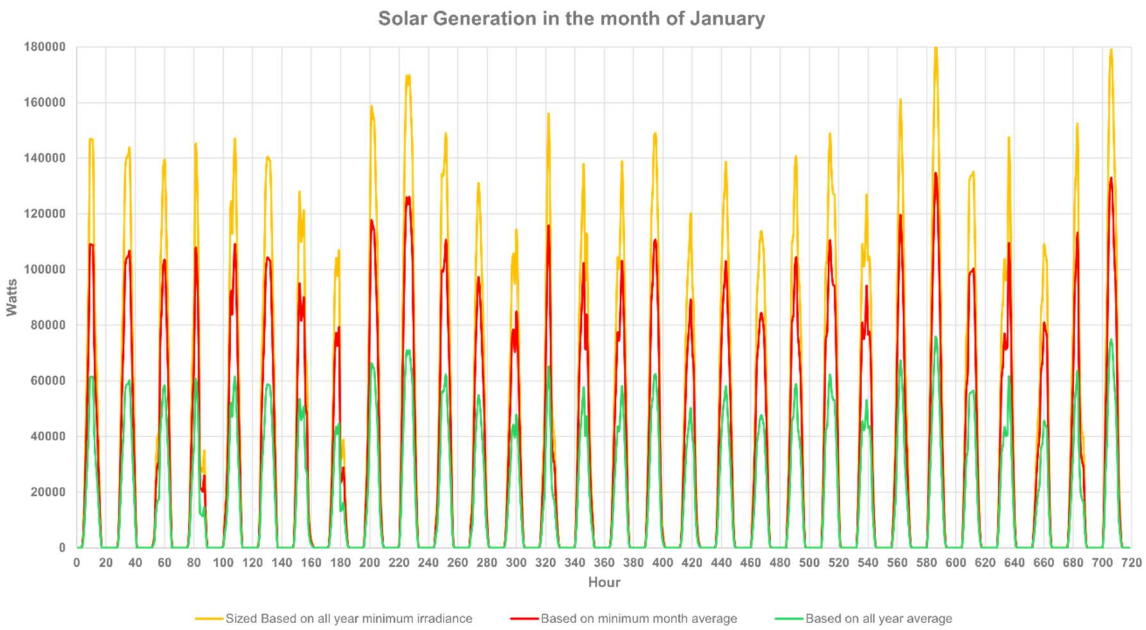

Figure 28: Generation capacity based on the three cases (100% PV).

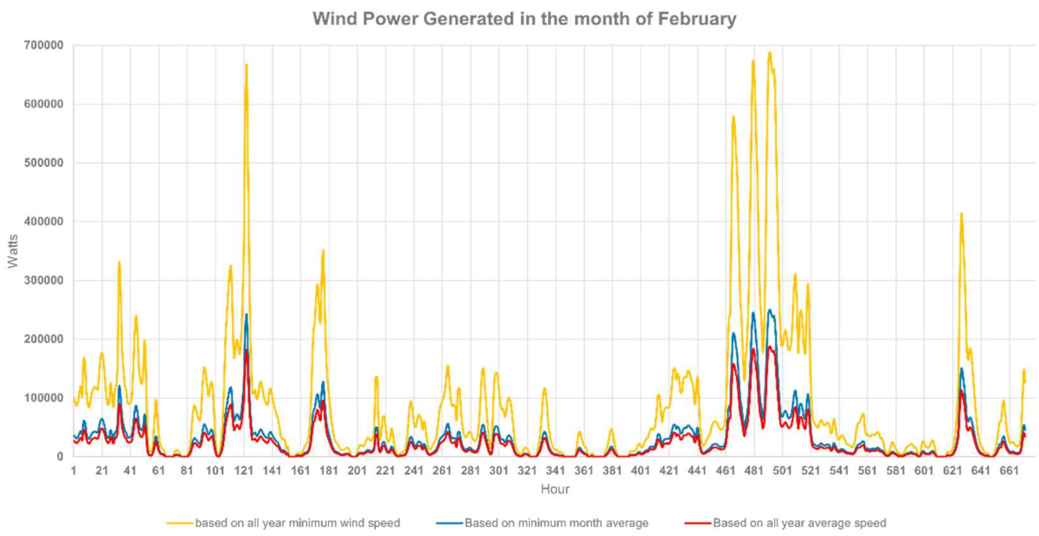

Figure 29: Generation capacity based on three cases (100% Wind power)

4.4 Energy Source Mixing Sensitivity

Given the intermittent nature of solar and wind resources, the study employs a hybrid energy system that combines these two sources to enhance power supply reliability. Various energy mix configurations are examined, and their performance is evaluated. Table 5 illustrates the different energy configurations under analysis.

The energy configurations performances are explored by checking the Supply-Demand Match score (SDMs) for the seasons experienced in Zambia. The analysis is done based on the all-year average available energy resources. The configuration with the highest Supply-Demand Match Score is selected for implementation.

Table 5: Energy Source Mix Configurations

Hybrid Energy Mix Configuration		
100% PV Generator	**100% Wind Generator**	**Scenario 1**
80kW	80kW	40kW PV + 40kW Wind
Scenario 2	**Scenario 3**	**Scenario 4**
60kW PV + 20kW Wind	30kW PV + 60kW wind	20kW PV + 60kW Wind

4.4.1.1 Wet Rainy Season

The energy resources during the wet and rainy seasons exhibit their lowest levels and are subject to analysis for various energy mix configurations. To initiate the supply-demand analysis, a non-hybrid power system solely reliant on either solar PV or wind power is first employed. The performances of these energy systems are depicted in Figures 30 and 31respectively. The intermittency nature of the energy resources results in periods without or low supply to meet the demand despite having periods with surplus energy as shown in Figure 31. The nature of the renewable energy resource(solar and wind) results in periods when the energy supply does not meet the energy demand indicating the inefficiency of a single energy source suggesting the need for a hybrid solution to minimise the period of low supply.

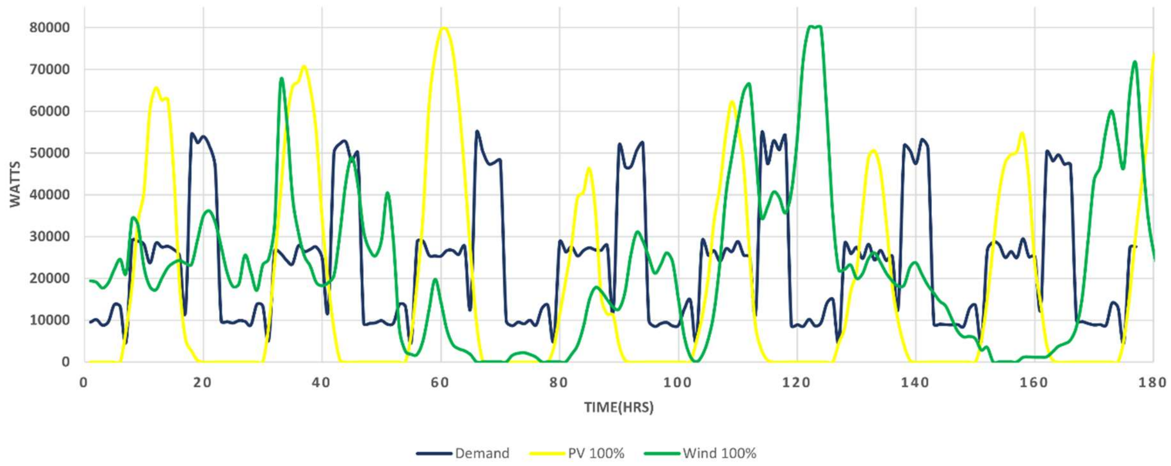

Figure 30: Non-hybrid energy system configuration supply vs demand during the wet rainy season

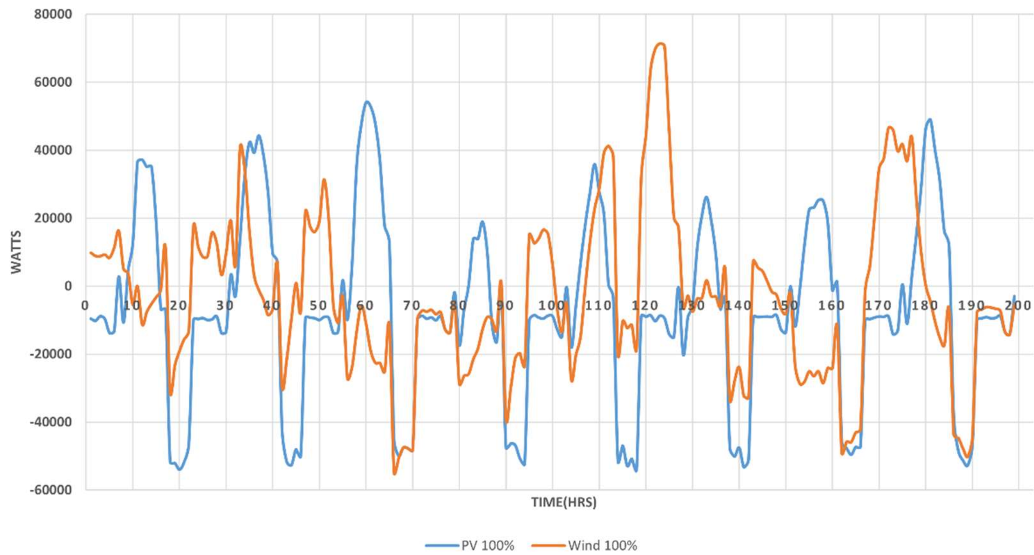

Figure 31: Surplus energy for non-hybrid system configurations for the wet rainy season

In an attempt to improve the reliability of the power system, hybrid configurations are introduced, and the Supply-Demand Matching Score (SDMs) is analysed for various energy mix configurations to identify the most reliable combination (see Figure 34). The objective is to assess the extent of power supply loss associated with each energy mix. This analysis serves as a basis for incorporating secondary energy sources, such as storage, to complement the existing system and address its inefficiencies. Table 6 shows the summary of the performance of the different configurations in the wet rainy season.

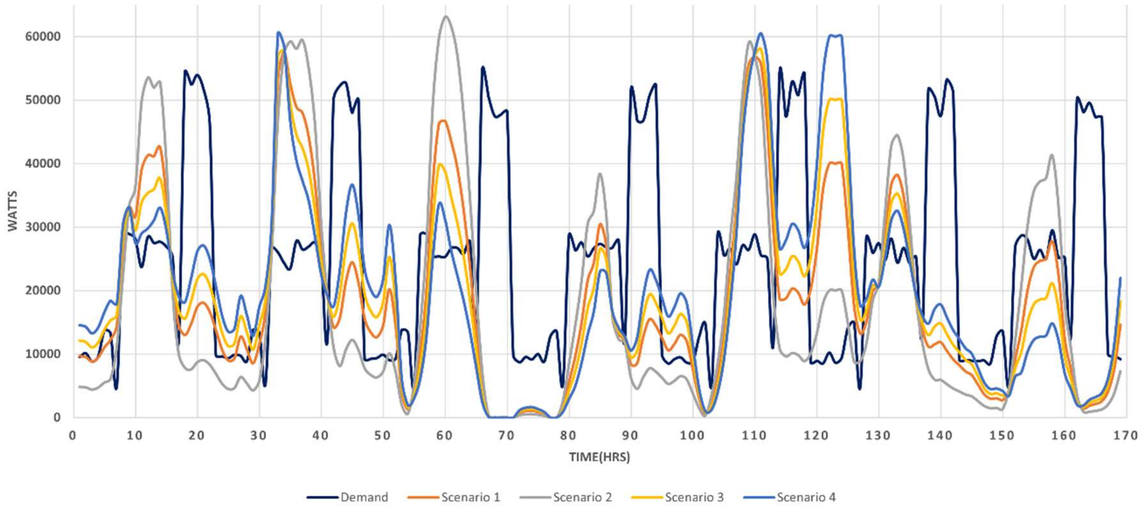

Figure 32: Hybrid energy mix configurations supply vs demand

Figure 32 shows the different energy mix ratios against the community energy demand and its clear that the supply-demand has improved to the single energy source employed earlier however there are still periods when the supply is lower than the energy demand although there are periods also with excess energy supply as shown in Figure 33.

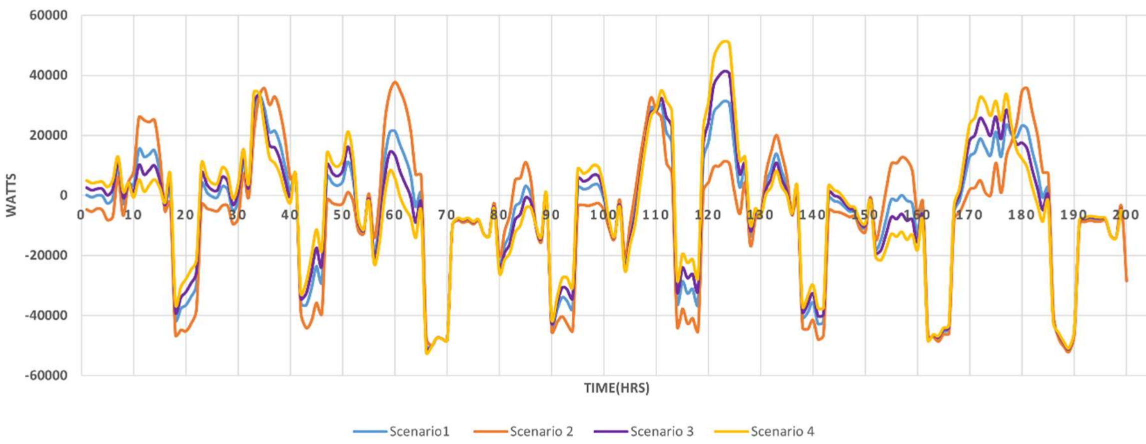

Figure 33: Surplus energy for hybrid energy mix configuration in the wet rainy season

A score of one in Figure 34 represents periods when the supply meets all the energy demand and any score below indicates low supply and the system is unable to meet the energy needs of the community. The score is determined by the available energy resources and following the nature of the energy resource, the score is never one throughout the operations of this season.

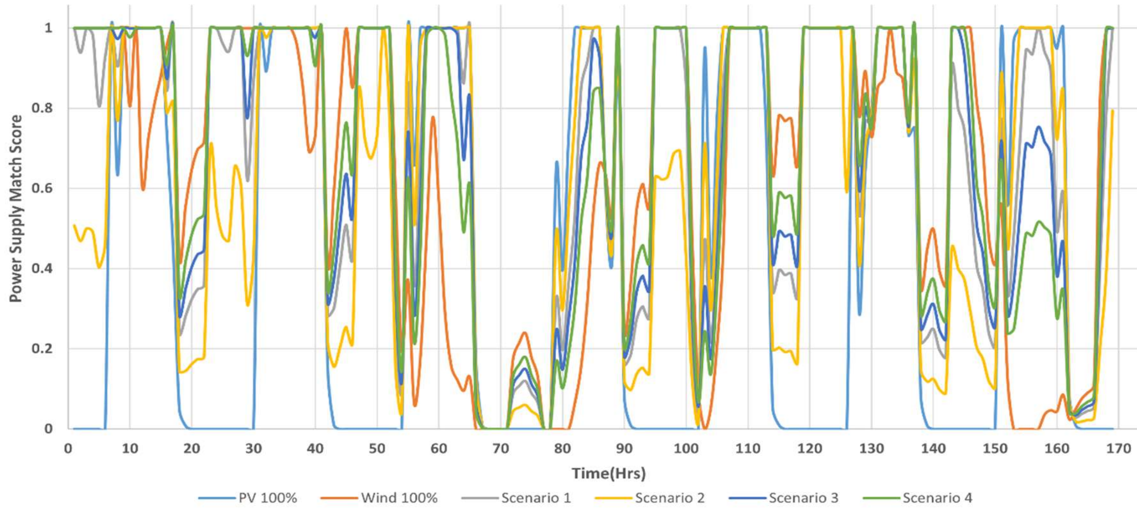

Figure 34: Supply-demand match score in the wet rainy season

The analysis reveals that scenario 1 exhibits the highest supply-demand score, while scenario 4 demonstrates the net energy deficit required to meet the demand consistently. Selecting the appropriate configuration depends on both factors such as the reliability of time matching between supply and demand, as well as the net deficit amount required to meet the energy demand.

Table 6: Wet rainy season performance

Configuration	SDMs	Net Energy (MWh)
100% PV	0.406	-6.448
100% Wind	0.519	-5.378
Scenario 1	0.607	-5.740
Scenario 2	0.554	-6.091
Scenario 3	0.605	-5.688
Scenario 4	0.588	-5.283

4.4.1.2 Dry Warm Season

During the analysis of the system's performance in the dry warm season, it is expected that the system will exhibit better performance, primarily because the energy resources available during this season surpass those available during the wet rainy season. An exploration of the non-hybrid system reveals that it exhibits higher energy production levels, with the system frequently reaching its capacity during the dry warm season more compared to the production observed during the wet rainy season, as depicted in Figure 35. The wind farm during this season performs far better due to the improved wind speeds allowing for more operation periods of the WTs as winds are mostly above the cut-in speeds of 2m/s for the selected wind turbine.

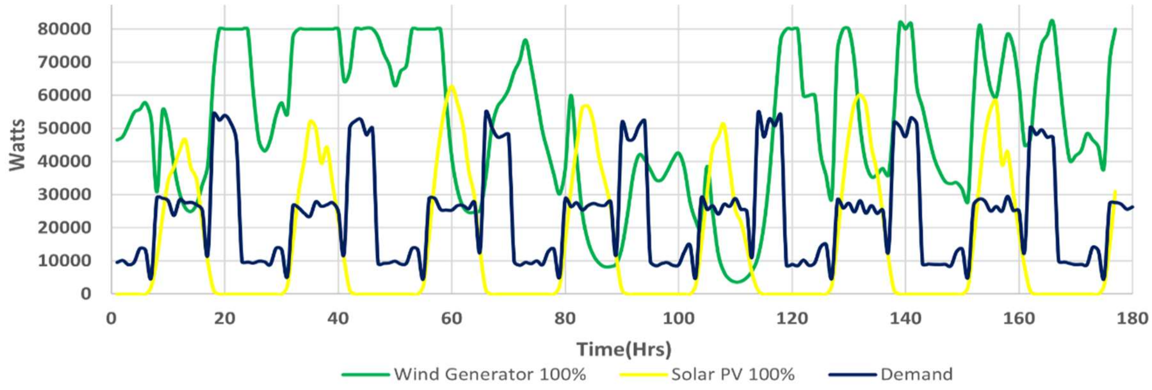

Figure 35: non-hybrid energy system configuration supply vs demand during the cool dry season

The increased availability of resources during the dry season results in higher net surplus energy and a better supply-demand match score than the wet rainy season, as shown in Figure 36. However, despite the abundant resources, the supply-demand match remains unreliable due to the intermittent nature of the energy source suggestion for secondary energy sources for a robust design.

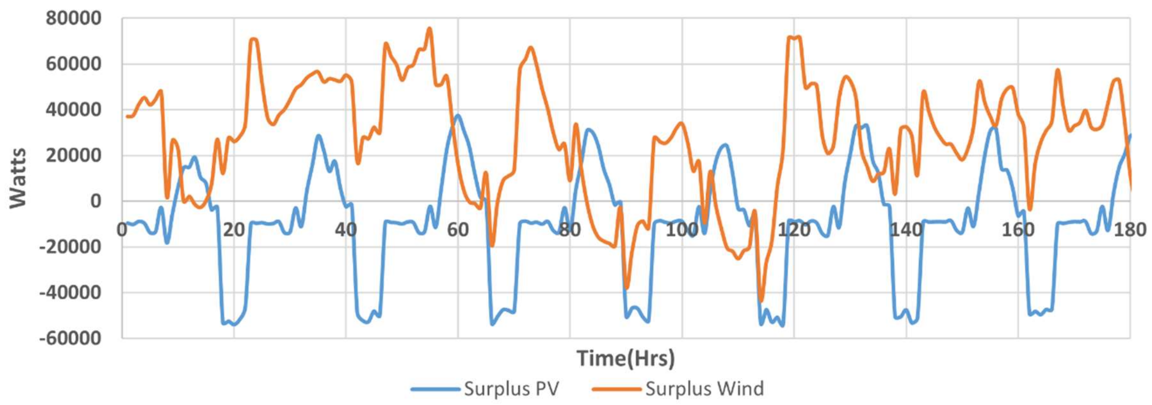

Figure 36:Surplus energy for non-hybrid system configurations for cool dry season

To enhance the supply-demand match and power supply reliability, various hybrid configurations are investigated for the summer period. Figure 37 illustrates the impact on the supply-demand matching for different configurations, and it is evident that the matching is significantly improved compared to the wet rainy season.

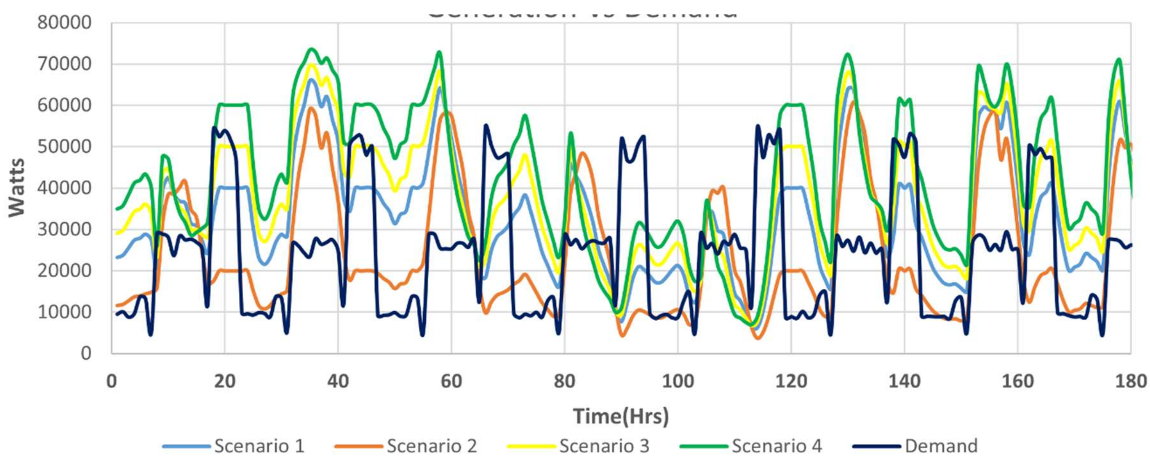

Figure 37:Hybrid energy system configuration supply vs demand during the cool dry season

The different hybrid energy mix ratios during the cool dry season yield a higher next surplus energy with the majority yielding positive net surplus energy as in Figure 38. However, the supply does not always meet the demand even during season as shown in Figure 39 hence suggesting that a secondary energy source is essential to design a robust autonomous energy system.

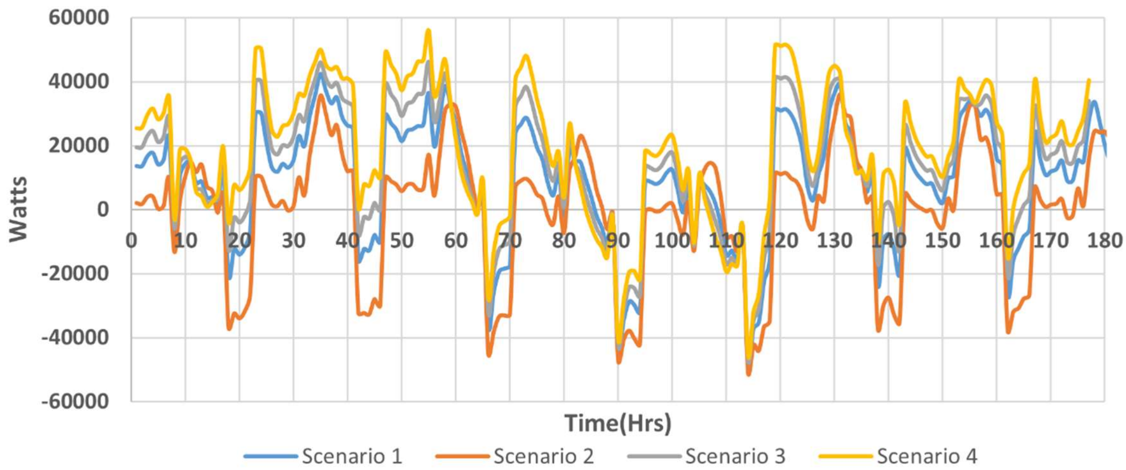

Figure 38:Surplus energy for hybrid system configurations in the cool dry season

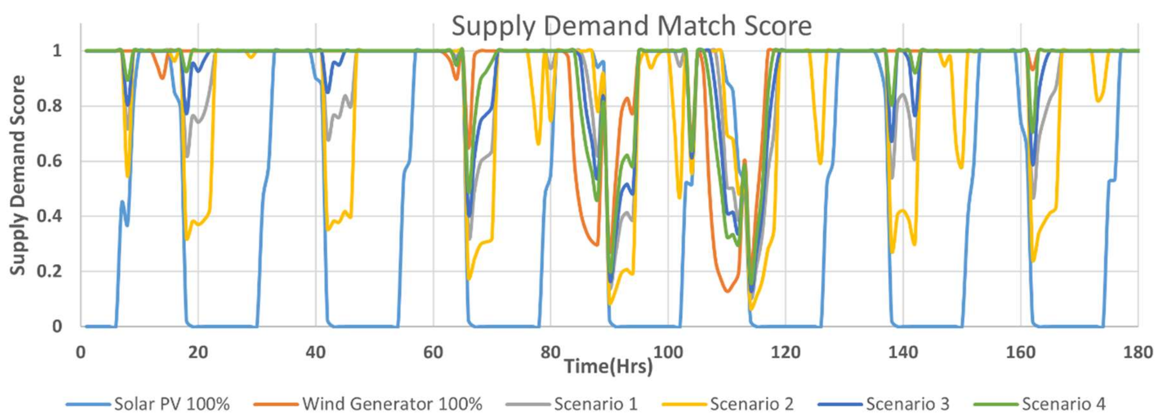

Figure 39: Supply-demand match score in the cool dry season

The system's overall performance is notably superior during the dry season compared to the wet season, as evidenced by a higher SDMs score of 0.881 in contrast to 0.607 during the wet season. Additionally, it is worth noting that most of the configurations result in a net positive surplus generation, as indicated in Table 7.

Table 7: Cool dry season performance

Configuration	SDMs	Net Energy (MWh)
Solar PV 100%	0.407	-6.10
Wind generator 100%	0.801	14.1
Scenario 1	0.861	3.94
Scenario 2	0.792	-1.06
Scenario 3	0.877	6.42
Scenario 4	0.881	8.99

5.0 Discussion, Limitations, Further Work & Conclusion

This chapter discusses the advantages of the adopted approach to the methodology for designing and optimising hybrid off-grid systems and gives a conclusion to the research. Section 5.1 gives an open discussion of the developed methodology and illustrated the capabilities of the methodology followed by section 5.2 which discusses the methodology and the limitations of the methodology while highlighting areas of improvement for designing an autonomous off-grid hybrid system. Section 5.3 highlights the conclusion of the research going through key aspects of the adopted methodology and proposes key future potential works that can be adopted in improving the methodology. The discussion presented in the chapter is meant to facilitate improvement in future research in developing off-grid hybrid autonomous power systems for rural communities.

5.1 Discussions

The adopted methodology focused on the demand and supply side of the power systems independently with the objectivity of optimising both parts of the power systems in terms of design. As in the demand side estimation discussed in section 3.1, an analysis is done to develop a tool with the ability to capture the switching behaviour of appliances. The developed tool allows the user to input the power rating of the appliances and the bias on the frequency of usage depending on the level of importance of the appliance operation. The developed tool also incorporated a percentage of probabilities in terms of when an appliance is likely to be on or off. This design methodology developed in section 3.1 accounts for diversity factors associated with appliance usage avoiding over-estimation of the energy demand. The developed methodology still allows for seasonal analysis of energy demand estimation for instance three scenarios are employed to check the effect of season on the energy demand.

The demand profiles shown in chapter four do not include thermal loads and to show seasonal effects on energy consumption thermal loads can be introduced and their operations defined depending on the required temperatures and the environmental temperature conditions. Zambia experiences low temperatures as low as 5°C during the winter period and average high temperatures of 30°C during the summer. Cooling becomes essential during the afternoon hours when there is the sun bright and shining during the summer and heating is essential during the night and early hours during the winter periods.

Assuming that the community household in the proposed community has hybrid (provide both cooling and heating) air condition units rated at 600W the energy demand profile with seasonal effects is observed in Figure 40. Thermal loads show a significant energy consumption with an increase of 60% during the winter and 181% during the summer in comparison to households without any thermal loads. The seasonal effects significantly affect the capacity sizing of the power system as shown in Table 8.

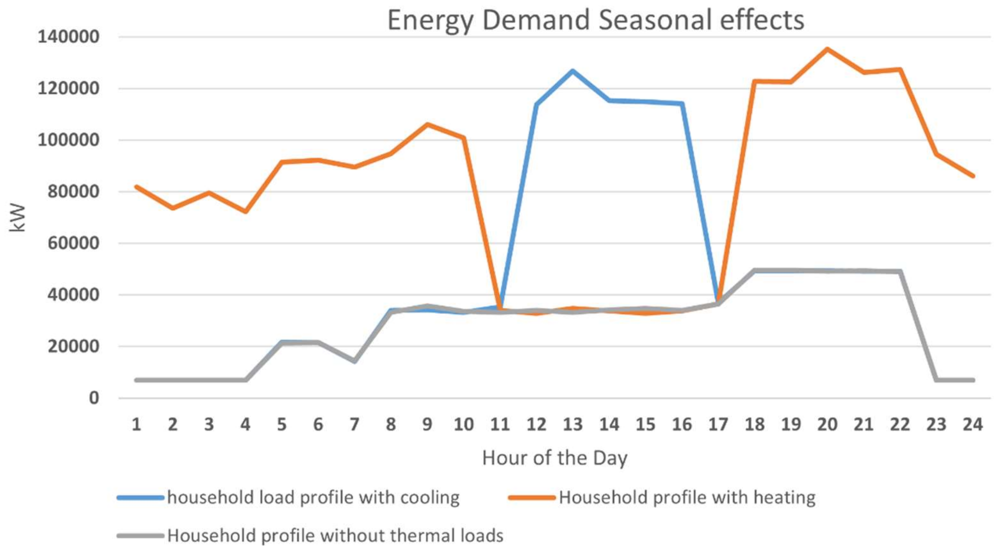

Figure 40:Illustration of seasonal effects on energy consumption

Table 8: Seasonal effects on energy consumption

Household load type	Daily households energy (kWh)	Increase in energy consumption(%)	Proposed plant capacity(kW)
No Thermal Loads	688,383	0%	78
With Cooling	1,104,180	60%	124.8
With Heating	1,935,780	181%	219.1

5.2 Project Limitation

The research attempts to establish a systematic approach for designing and optimizing off-grid power systems while conducting a comprehensive performance analysis of the proposed system. The methodology presented in this study not only offers valuable insights but also opens avenues for future research to enhance and refine the development of off-grid autonomous power systems. However, it is essential to acknowledge that the current study does not entirely encompass all aspects required for the designing of a fully robust autonomous off-grid system. A summary of the advantages and limitations of the adopted methodology in designing and optimizing the off-grid system is shown in Table 9.

Table 9: Summary of the pros and cons of the developed study methodology

The Research Adopted methodology	
Advantage	**Disadvantage**
Hybrid system sizing methodology	No storage option investigations
Incorporates demand forecast	No analysis of seasonal effects on demand
Incorporates behavioural effects on energy consumption	No investigation on the effect of electricity access on energy consumption
Seasonal performance analysis	Does not carry an economic analysis
Explores the overall system performance	No technical design analysis

The methodology adopted investigates the seasonal effects on the system performance and analyses the supply-demand match however the study checks the performance of the system using a static energy profile. In reality, energy consumption is dependent on the season for example use of air conditioning and the energy consumed will depend on the temperature conditions. The study does not carry out the seasonal energy consumption effects and this must be considered for improvement of the design methodology in any future works to capture the dynamics of the energy consumption.

Access to electricity triggers a sudden increase in energy consumption[45] and no investigation on the possible impact on the energy demand due to energy access is done in the presented methodology of the study. Due to time constraints, the study does not explore the impact of storage on the reliability of the power system nor does the study investigate any further secondary energy option to mitigate the periods of low supply. In addition, no financial modelling or analysis is investigated in the design process adopted in the study.

5.3 Future Works and Conclusion

The methodology adopted opens opportunities for future works for an improved design methodology. The potential future areas of research are highlighted below, and the tangible advantages of the developed methodology are explained too.

5.3.1 Future works

The proposed design methodology opens avenues to the development of robust and autonomous off-grid systems. Potential future areas of study to enhance the developed methodology include:

- Supply-demand management: This thesis does not look at any management strategies for the operations of the off-grid power systems for rural communities and this leaves a gap for future research on management strategies like the following:
  - Load shifting: This is a potential area to explore to optimise off-grid performance by developing a program or schedule for shifting demand to times when there is a surplus energy supply.
  - Storage: The research does not explore any potential i.e (battery, thermal, etc.) storage options suggesting future research to explore the various energy storage options to select the best options for the off-grid system under consideration
  - Dispatch strategy: Potential areas of research is developing a methodology for energy dispatching i.e (diesel) adapted to the load data and off-grid system configuration
- Financial modelling: There is no financial analysis undertaken in this study and this proposes a need to carry out financial analysis in the future and this may include:
  - Business strategy and management
  - Capital costing and maintenance analysis i.e., levelized cost of energy
- Technical analysis: Further technical analysis can be taken on the following:
  - Voltage and frequency analysis

- Power control
- Advanced mathematical modelling of power system components.

5.3.2 Conclusion

The adopted methodology develops an energy profile generator that captures the stochastic nature of energy usage. The methodology developed in generating the demand profile demonstrates energy usage behavioural patterns in the switching of associated appliances. The research methodology adopts a hybrid approach in power system capacity sizing and investigates the power system reliability based on the analysis of the power loss probability based on different energy mix configurations.

The developed methodology is applied to a community in Zambia and the analysis demonstrated that a hybrid solution is more reliable with a higher supply-demand match score. The developed methodology demonstrates that performance analysis is critical and subject to the particular site of consideration and for application in the research it demonstrated how seasons and environmental conditions affect the production and reliability of off-grid renewable systems. Cool dry and warm with clear weather conditions yielded higher SDMs compared to wet weather conditions.

To sum it all the developed methodology is successful at achieving the following design features:

- Captures stochastic behaviour of energy usage.
- Considers energy usage diversity factors.
- Has ability to aggregate energy profiles.
- Gives control to the user to define the appliance switching function.
- Adopts a hybrid sizing technique and explores the effect of energy source mix configurations on performance.
- Defines a performance matrix and explores the system performance.

This research is a positive contribution towards increasing energy access through the design of off-grid systems and serves as an exciting methodology that can be improved in future studies to improve the design of off-grid hybrid systems.

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7.0 Appendices

I. Community electrical appliance usage

User Type	No.	Appliance	Qty	Rate (W)	Connected Load(W)	Window I Time(hrs)	Window II	Window III
Grocery Shop	11	**Inside Lights**	**2**	**10**	**20**	**[05 - 08]**	**[17 - 19]**	**N/A**
		Outdoor Lights	**1**	**15**	**15**	**[17 - 06]**	**N/A**	**N/A**
		Fridge	**1**	**100**	**100**	**[01 - 24]**	**N/A**	**N/A**
Barbershop	**07**	**Radio**	**1**	**60**	**60**	**[08 - 18]**	**N/A**	**N/A**
		Cutting Machine	**2**	**50**	**100**	**[08 – 18]**	**N/A**	**N/A**
Church	**01**	**Inside Lights**	**6**	**10**	**60**	**[05 – 08]**	**N/A**	**N/A**
		Outdoor Lights	**4**	**15**	**60**	**[17 - 06]**	**N/A**	**N/A**
School	**04**	**Siren**	**01**	**20**	**20**	**[08 – 16]**	**N/A**	**N/A**
		Inside Lights	**25**	**10**	**250**	**[08 – 16]**	**N/A**	**N/A**
		Outdoor lights	**10**	**15**	**150**	**[18 – 06]**	**N/A**	**N/A**
		Desktop	**04**	**150**	**600**	**[08 – 16]**	**N/A**	**N/A**
		Printer	**01**	**120**	**120**	**[08 – 16]**	**N/A**	**N/A**
Health Centre	**01**	**Inside Lights**	**08**	**10**	**80**	**[1 – 24]**	**N/A**	**N/A**
		Outdoor Lights	**06**	**15**	**90**	**[18 – 08]**	**N/A**	**N/A**
		Microscope	**01**	**50**	**50**	**[08 – 16]**	**N/A**	**N/A**
		Blood Analyser	**01**	**60**	**60**	**[08 – 16]**	**N/A**	**N/A**
		Examination Lamp	**01**	**50**	**50**	**[08 – 16]**	**N/A**	**N/A**
		Vaccine Fridge	**01**	**150**	**150**	**[01 – 24]**	**N/A**	**N/A**
		Desktop	**01**	**150**	**150**	**[08 – 16]**	**N/A**	**N/A**

Police Post	**01**	**Desktop**	**02**	**150**	**300**	**[08 - 16]**	**N/A**	**N/A**
		Printer	**01**	**120**	**120**	**[08 - 16]**	**N/A**	**N/A**
		Inside Lights	**04**	**10**	**40**	**[05 – 07]**	**[17 – 19]**	**N/A**
		Outdoor Lights	**02**	**15**	**30**	**[17 - 06]**	**N/A**	**N/A**
House	**231**	**TV Set**	**01**	**120**	**120**	**[08 - 16]**	**[18 – 22]**	**N/A**
		Radio	**01**	**50**	**50**	**[08 - 16]**	**N/A**	**N/A**
		Inside Lights	**04**	**10**	**40**	**[05 - 07]**	**[17 – 22]**	**N/A**
		Outdoor Light	**02**	**15**	**30**	**[18 – 06]**	**N/A**	**N/A**
		Phone	**03**	**10**	**30**	**[5 – 22]**	**N/A**	**N/A**

II. Demand Profile MATLAB Code

```
% Prompt the user to input the number of users
numUsers = input('Enter the number of users: ');

% Prompt the user to input the number of appliances
numAppliances = input('Enter the number of appliances: ');

% Define the number of hours
numHours = 24;

% Initialize arrays to store the profiles for each user and the hourly
consumption
userProfiles = cell(numUsers, 1);
userHourlyConsumption = zeros(numUsers, numHours);

% Prompt the user to input the power rating and windows for each
appliance
for i = 1:numAppliances
    fprintf('Appliance %d:\n', i);
    applianceRating = input('Enter the power rating for the appliance:
');

    % Prompt the user to input the number of windows for the current
appliance
    numWindows = input('Enter the number of windows for the appliance:
');

    % Initialize an array to store the windows for the current appliance
    windows = zeros(numWindows, 3);

    % Prompt the user to input the window start, end indices, and
percentage of ones for each window
```

```
    for j = 1:numWindows
        fprintf('Window %d:\n', j);
        windows(j, 1) = input('Enter the window start index: ');
        windows(j, 2) = input('Enter the window end index: ');
        windows(j, 3) = input('Enter the percentage of ones within the
window: ');
    end

    % Loop over each user
    for user = 1:numUsers
        % Initialize the profile array for the current appliance
        profile = zeros(1, numHours);

        % Loop over each window for the current appliance
        for window = 1:numWindows
            windowStart = windows(window, 1);
            windowEnd = windows(window, 2);
            percentage = windows(window, 3);

            % Generate random on/off states within the current window
            windowLength = windowEnd - windowStart + 1;
            numOnes = round(windowLength * (percentage / 100));

            % Generate an array of zeros with the size of the current
window
            states = zeros(1, windowLength);

            % Generate random indices for the ones within the current
window
            randomIndices = randperm(windowLength, numOnes);

            % Set the corresponding indices to ones within the current
window
            states(randomIndices) = 1;

            % Assign the generated states to the profile array within
the current window
            profile(windowStart:windowEnd) = states;
        end

        % Multiply the profile array with the appliance power rating
        profile = profile * applianceRating;

        % Store the profile for the current appliance
        userProfiles{user}{i} = profile;

        % Calculate the hourly consumption for the current user
        userHourlyConsumption(user, :) = userHourlyConsumption(user, :)
+ profile;
    end
end

% Calculate the total hourly consumption for all users
totalHourlyConsumption = sum(userHourlyConsumption, 1);

% Export the hourly consumption for each user and the aggregated hourly
consumption to a single CSV file
combinedConsumption = [userHourlyConsumption; totalHourlyConsumption];
combinedConsumptionFilename = 'combined_hourly_consumption.csv';
csvwrite(combinedConsumptionFilename, combinedConsumption);

% Display a message indicating successful export
```

```
disp('Hourly consumptions exported successfully.');

% Display the hourly consumption for each user
for user = 1:numUsers
    fprintf('Hourly consumption for User %d:\n', user);
    disp(userHourlyConsumption(user, :));
end
```

III. Demand Growth MATLAB Code

```
% Prompt the user to enter the Excel file name for initial data
prompt = 'Enter the Excel file name for initial data (including the
extension): ';
filenameInitial = input(prompt, 's');

% Prompt the user to enter the column index of the dependent variable
prompt = 'Enter the column index of the dependent variable: ';
dependentVarIndex = input(prompt);

% Prompt the user to enter the column indices of the control variables
prompt = 'Enter the column indices of the control variables [var1, var2,
...]: ';
controlVarsIndices = input(prompt);

% Read the initial data from the Excel file
dataInitial = xlsread(filenameInitial);

% Extract the initial dependent variable and control variables from the
data
dependentVar = dataInitial(:, dependentVarIndex);
controlVars = dataInitial(:, controlVarsIndices);

% Perform the initial polynomial regression
initialOrder = 0;
accuracyScore = 0;

while true
    % Prompt the user for the order of the polynomial regression model
    prompt = 'Enter the order of the polynomial regression model (enter
0 to exit): ';
    polynomialDegree = input(prompt);

    if polynomialDegree == 0
        disp('Exiting the program.');
        break;
    end

    % Check if the sizes of the input vectors match
    if ~isequal(size(dependentVar, 1), size(controlVars, 1))
        error('Input vectors must have the same number of rows.');
    end

    % Perform the polynomial regression
    X = ones(size(controlVars, 1), 1);
    for degree = 1:polynomialDegree
        X = [X, controlVars.^degree];
    end
```

```
    coefficients = X \ dependentVar;

    % Calculate the accuracy score (R-squared)
    predicted = X * coefficients;
    ssr = sum((predicted - dependentVar).^2);
    sst = sum((dependentVar - mean(dependentVar)).^2);
    accuracyScore = 1 - (ssr / sst);

    disp('Accuracy Score (R-squared) for Initial Regression:');
    disp(accuracyScore);

    % Prompt the user to decide whether to proceed with the trained
model
    prompt = 'Do you want to proceed with this trained model? [Y/N]: ';
    choice = input(prompt, 's');

    if upper(choice) == 'Y'
        initialOrder = polynomialDegree;
        break;
    end
end

if initialOrder == 0
    disp('Exiting the program.');
else
    disp('Continuing with the trained model.');

    % Prompt the user to enter the Excel file name for new control
variables
    prompt = 'Enter the Excel file name for new control variables
(including the extension): ';
    filenameNew = input(prompt, 's');

    % Read the new control variables from the Excel file
    dataNew = xlsread(filenameNew);

    % Prompt the user to enter the column indices of the new control
variables
    prompt = 'Enter the column indices of the new control variables
[var1, var2, ...]: ';
    newControlVarsIndices = input(prompt);

    % Extract the new control variables from the data
    newControlVars = dataNew(:, newControlVarsIndices);

    % Check if the size of the new control variables matches the number
of control variables in the model
    if ~isequal(size(newControlVars, 2), size(controlVars, 2))
        error('Number of new control variables does not match the
model.');
    end

    % Perform the prediction on the new control variables using the
trained model
    newX = ones(size(newControlVars, 1), 1);
    for degree = 1:initialOrder
        newX = [newX, newControlVars.^degree];
    end

    predict = newX * coefficients;

    % Display the predicted values for the new control variables
```

```
    disp('Predicted Values for New Control Variables:');
    disp(predict);
end
```

IV. PV Sizing Code

```
% Prompt the user to input the parameters
dailyConsumption = input('Enter daily consumption (kWh/day): ');
dailyIrradiance = input('Enter daily irradiance available (kWh/m^2/day):
');
pvEfficiency = input('Enter PV efficiency: ');
deratingFactor = input('Enter derating factor: ');
pvModuleArea = input('Enter PV module area (m^2): ');
pvModulePower = input('Enter PV module power rating (kW): ');
desiredAutonomy = input('Enter desired autonomy (in days): ');
batteryDoD = input('Enter battery depth of discharge (DoD) limit (in
percentage): ');

% Calculate PV area required with derating factor
pvAreaRequired = dailyConsumption / (dailyIrradiance * pvEfficiency *
deratingFactor);

% Calculate number of PV modules required
numPvModules = ceil(pvAreaRequired / pvModuleArea);

% Calculate total solar plant area required
solarPlantArea = numPvModules * pvModuleArea;

% Calculate battery storage capacity required
batteryCapacityRequired = (dailyConsumption * desiredAutonomy) / (1 -
(batteryDoD/100));

% Display the results
fprintf('PV area required: %.2f m^2\n', pvAreaRequired);
fprintf('Number of PV modules required: %d\n', numPvModules);
fprintf('Total solar plant area required: %.2f m^2\n', solarPlantArea);
fprintf('Battery storage capacity required: %.2f kWh\n',
batteryCapacityRequired);
```

V. Wind Sizing Code

```
% Wind Farm Sizing with User Inputs

% Prompt the user for input parameters
energyConsumption = input('Enter the daily energy consumption in kWh:
');
turbinePowerCoeff = input('Enter the turbine power coefficient: ');
averageWindSpeed = input('Enter the average wind speed in m/s: ');
cutInWindSpeed = input('Enter the cut-in wind speed in m/s: ');
cutOutWindSpeed = input('Enter the cut-out wind speed in m/s: ');
efficiencyFactor = input('Enter the efficiency factor (0-1): ');
hubHeight = input('Enter the hub height in meters: ');

% Constants
```

```
airDensity = 1.225; % Air density in kg/m^3

% Convert energy consumption to Wh
energyConsumption = energyConsumption * 1000; % Convert from kWh to Wh

% Calculate cut-in and cut-out wind power
cutInWindPower = 0.5 * airDensity * (cutInWindSpeed^3);
cutOutWindPower = 0.5 * airDensity * (cutOutWindSpeed^3);

% Calculate swept area based on daily energy consumption and average
wind speed
sweptArea = (energyConsumption) / (turbinePowerCoeff * 24 *
((averageWindSpeed^3) - (cutInWindSpeed^3)));

% Calculate rotor radius based on swept area
rotorRadius = sqrt(sweptArea / pi);

% Calculate rated power
ratedPower = (turbinePowerCoeff * sweptArea * ((averageWindSpeed^3) -
(cutInWindSpeed^3))) / 24;

% Calculate actual power output
actualPowerOutput = ratedPower * efficiencyFactor;

% Calculate number of blades
numberOfBlades = input('Enter the number of blades: ');

% Adjust swept area based on number of blades
sweptArea = sweptArea * numberOfBlades;

% Adjust rated power based on efficiency and number of blades
ratedPower = actualPowerOutput / efficiencyFactor;

% Display results
fprintf('Daily Energy Consumption: %.2f kWh\n', energyConsumption /
1000);
fprintf('Average Wind Speed: %.2f m/s\n', averageWindSpeed);
fprintf('Cut-in Wind Speed: %.2f m/s\n', cutInWindSpeed);
fprintf('Cut-out Wind Speed: %.2f m/s\n', cutOutWindSpeed);
fprintf('Swept Area: %.2f m^2\n', sweptArea);
fprintf('Rotor Radius: %.2f m\n', rotorRadius);
fprintf('Rated Power: %.2f kW\n', ratedPower);
fprintf('Actual Power Output: %.2f kW\n', actualPowerOutput);
fprintf('Efficiency Factor: %.2f\n', efficiencyFactor);
fprintf('Number of Blades: %d\n', numberOfBlades);
fprintf('Hub Height: %.2f m\n', hubHeight);
```