UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

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Title of Project: **Technical Assessment of Solar Home System (SHS) Integration into the Power Grid**

A Case Study of Rwanda

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MASTERS OF SCIENCE IN ELECTRICAL POWER SYSTEM

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Kigali-Rwanda

Declaration

I, the undersigned, certify that this project proposal is my original work and has not been submitted for a degree at the University of Rwanda or any other university. All sources for information used in the thesis shall be thoroughly recognized and referenced.

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Thesis Co-supervisor

APPROVAL

Submission Date: **…/…..../ 2025**

This project has been submitted for examination approved by university Supervisor

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Thesis Supervisor Signature ……………...

Acknowledgment

My sincerely thanks and appreciations go to:

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LISTS OF ABREVIATIONS & ACRONYMS

A: Ampere

AC: Alternating current

ACEESD: African Center of Excellence in Energy for Sustainable Development

CSP: Concentrated Solar Power

CSCR: Composite Short Circuit Ratio

DC: Direct Current

DG: Diesel Generator

GHG: Green House Gases

LFC: load frequency control

MPPT: Maximum power point tracking

NEP: National electrification plan

NST1: National Strategy for Transformation

PV: Photovoltaic

PID: proportional integral derivative

RE: Renewable Energy

REG: Rwanda Energy Group Ltd

SHS: Solar Home Systems

SCR: Short Circuit Ratio

SDHW: Solar domestic hot water systems

STATCOM: Static Synchronous Compensators

ESS: Energy Storage Systems

IEMS: Intelligent Energy Management Systems

UR: University of Rwanda

V: Volt

W: Watt

ABSTRACT

This project work investigates the technical aspects of integrating Solar Home Systems (SHS) into the power grid, with a particular focus on Rwanda's energy infrastructure. As the demand for sustainable energy solutions grows, the potential of decentralized renewable energy sources, particularly photovoltaic (PV) systems, has gained significant attention. This study explores the impact of integrating both individual PV systems and a larger-scale distribution of multiple PV units within the grid. The simulation results are derived from three different software tools HOMER Pro, MATLAB version 2024b and Dig SILENT Power Factory. Firstly, the integration of a 5-kW peak PV system into the grid is analyzed using HOMER Pro software, enhancing the system's efficiency to maximize energy production, economic analysis, cost, and efficiency. The results provide insights into the feasibility of small-scale PV installations for rural and off-grid communities in Rwanda, evaluating factors such as energy demand, system size, and grid compatibility. Secondly, a more extensive simulation is conducted using Dig SILENT Power Factory, where the distributed PV systems are connected to the power grid with bus bars. The voltage profile and load flow analysis are performed to assess the grid's ability to accommodate these decentralized PV systems without compromising stability or voltage regulation. The study also addresses the technical challenges of voltage fluctuations, reactive power control, and integration of PV systems. The findings highlight the potential benefits and challenges of SHS integration, particularly with regard to grid stability, energy distribution, and the technical requirements for efficient power flow management. The thesis concludes by recommending the integration of PV systems into Rwanda's grid network, suggesting policies and technical measures to enhance the reliability, sustainability, and scalability of renewable energy solutions in the country.

CHAPTER ONE: INTRODUCTION

1.1 Background

The rising demand for energy and the exhaustion of raw materials used for its production have made energy supply a significant global challenge. Various strategic measures have been implemented, including the use of non-fossil power plants and renewable energy sources such as solar, wind, and hydropower, to replace fossil fuels. The advancement and utilization of renewable energy are becoming increasingly important[1].

Rwanda has made great progress in the energy sector during the last decade. Despite great achievements, a large percentage of the population continues to lack access to reliable electricity. The Rwandan government has set lofty goals for achieving universal access to energy by 2024, concentrating on both grid extension and off-grid solutions. By the end of June 2023., 71.9% of Rwandan households had access to electricity. These include 53.6% of households having access to the nation grid, while 18.3% are connected with off-grid system, including solar home systems (SHS), which emerged as a critical technology for increasing power availability to rural and remote areas[2]. After evaluating the state of power connections in every sector across the country and taking into account the standards set forth in the 2022 NEP amendment, it was discovered that the following had changed: Sixty-two percent of villages are on the grid (Grid Extension and Fill-in), representing 9,664 out of 14,816 villages, while 34.35% remain in the off-grid zone. Additionally, some villages are in the process of relocation due to being situated in high-risk areas, while others are located in regions designated for major agricultural investments, such as tea plantations[3].

1.2 The Role of Solar Home Systems (SHS)

The solar home system are decentralized energy systems that provide electricity to individual homes via solar panels, battery storage, and basic appliances such as lights, phone chargers, and radios. These systems have been popular in Rwanda due to their price, ease of installation, and ability to provide immediate electricity access to households far from the national grid[3].

The Government policies, private sector investments, and foreign development programs contributed to Rwanda's quick growth in the SHS market. Companies in this industry have developed novel business models, such as pay-as-you-go (PAYG) systems, which allow customers to pay for energy in small, manageable installments. This has made SHS more accessible to low-income households, hastening their uptake[4].

1.3 Integration into the National Grid

As Rwanda's electrification efforts progress, the integration of off-grid systems like SHS into the national grid becomes an essential consideration. This integration can provide a pathway for transitioning households from standalone systems to grid-connected solutions, enhancing energy reliability and enabling the use of more energy-intensive appliances[5]. However, integrating SHS into the existing power grid presents various technical challenges that need to be systematically assessed to ensure successful implementation. In this project work, it will focus on technical aspect to assess the feasibility of integration the SHS that are currently installed in Rwanda. Currently we have more than 12 MWp SHSs capacity installed countrywide with the total energy generated daily is around 40.5 MWh[6]. The generated energy is not fully utilized because those systems get full charged in few hours in a day and the remaining generated energy are being wasted. This project will analyse the possibility of how that energy that is being waste can be injected to the grid.

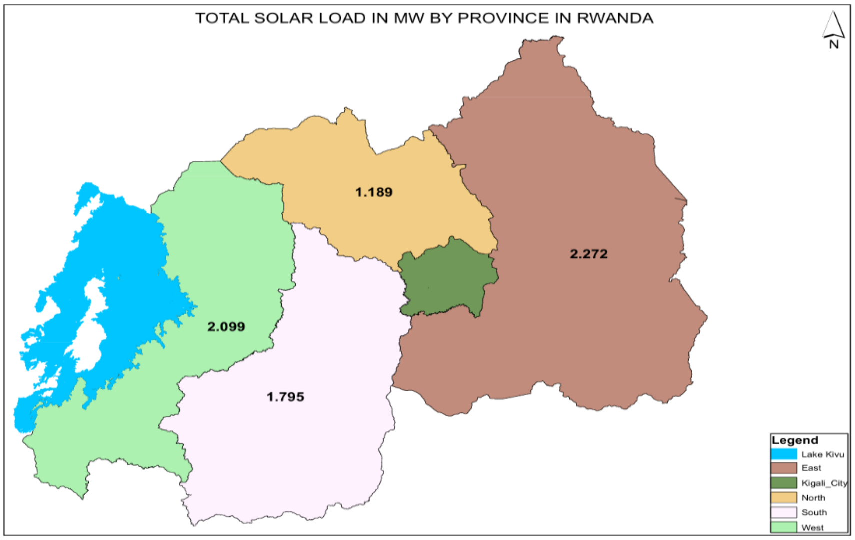


Figure 1. 1:Total solar generation in Rwanda by province in MW [4]

1.4 Basic Concepts

To comprehend the challenges of integrating Solar Home Systems (SHS) into a national power grid, it is crucial to understand key foundational concepts. These concepts form the basis for technical, regulatory, and socio-economic discussions on renewable energy integration. This section offers an overview of these fundamental principles, which will be examined in more detail within the Rwandan context.

1.4.1 Solar architecture

The solar architecture refers to an architectural strategy that emphasizes incorporating solar technologies into building design in order to successfully capture solar energy[7]. This thesis maximizes energy efficiency through the integration of modern technologies with architectural components. Active solar systems, intelligent control techniques to maximize solar radiation, and passive solar designs that capture solar energy without the need for active technology are all integrated into solar architecture. Designing sustainable and energy-efficient buildings that will assist lower energy use and greenhouse gas emissions while providing building occupants with the highest level of comfort is the goal of solar architecture[7].

1.4.2 Active and Passive Solar Systems

Solar architecture is an eco-friendly design strategy that uses local climate conditions to improve indoor comfort. Rather than relying on expensive and environmentally harmful artificial energy sources, this approach focuses on sustainability[8]. Unlike conventional building practices that treat climate as an obstacle, solar design aims to harmonize structures with their natural surroundings. There are two ways of exploiting the natural resource energy: Passive and Active. You can also combine the two as the third way, that one is called hybrid system. Solar systems are techniques for harnessing and converting sunlight into energy for a building's use. It can serve various purposes, such as heating, water heating, air heating, and electricity generation. Both active and passive solar systems fulfil the same purpose but utilize different technologies[9].

Table 1. 1:Advantages and disadvantages of Solar Systems [7]

Solar system	Advantages	Disadvantages
Active	➢ The benefits of mechanical systems include decreased carbon footprint, enhanced efficiency, larger capacity, installation on existing structures, and greater control over the use of energy.	High costs and maintenance demands, space limitations, dependence on external resources for operation, unattractive building aesthetics, and potential ice damage risks.
Passive	➢ Environmentally friendly solution that do not require external solar, no maintenance required, Cost effective, aesthetically appealing	The disadvantages of passive systems include decreased efficiency, inability to retrofit, and the overheating risk.
Hybrid	➢ Combines benefits of both systems, improves energy efficiency, lowers emissions, enhances home comfort and Lowers energy costs.	Complexity and greater installation expenses.

1.5 Challenges and benefits of SHS integration

The Integration of solar home system offers significant benefits such as reduced electricity bills, environmental sustainability, and potential energy independence, but it also presents challenges related to initial cost, weather dependency, and grid connection complexities depending on location and system design[10].

1.5.1. Benefits of Solar Home System Integration

As the impact of Renewable Energy Grid integration has been proven, the benefits can be divided into three categories: social, environmental, and economic. Second, Renewable Energy technologies produce no fossil fuel emissions; hence, integrating them will help fossil fuel power production facilities cut their CO2 emissions by reducing the quantity of power they produce[11]. Figure 1.2 illustrates the overall picture of how solar energy can be incorporated into the grid in home situations using grid tie inverters.

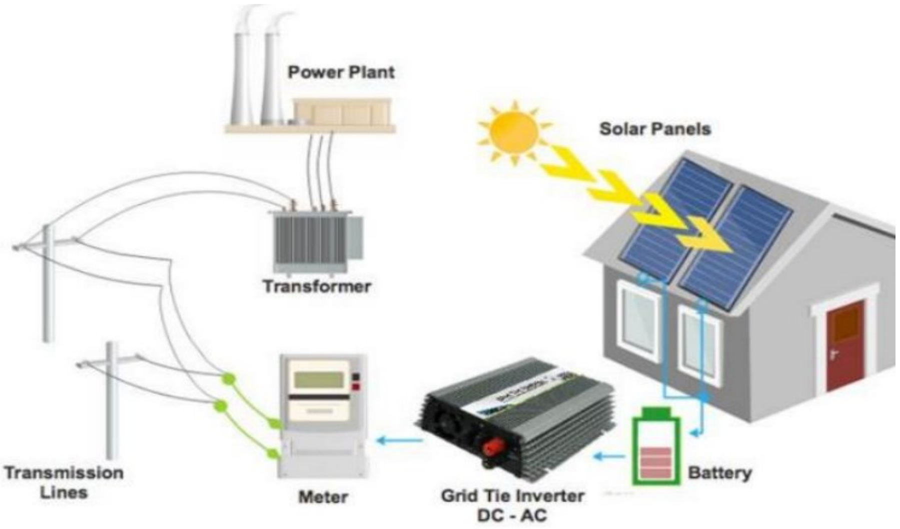


Figure 1. 2:General integrating solar system in residential[12]

The cost savings, environmental impact, energy independence and low maintenance are key benefit of the system. By producing power directly from sunshine, homes can significantly reduce their reliance on the grid, resulting in lower electricity bills over time. Solar energy is a clean, renewable source that helps to lower carbon footprint and mitigate climate change.

Depending on the system size, households can achieve partial or complete energy independence from the grid, ensuring power even during outages. Installing a solar system might potentially raise the market value of a home because of its perceived sustainability and cost-saving qualities. Solar panels require little maintenance once installed.

1.5.2 Challenges of Solar Home System Integration

The majority of renewable energy sources rely on unregulated resources. In other words, the energy generated by RE comes from sources of nature, such as wind, sunlight, & ocean waves. This type of information enables us to understand how sporadic and irregular RE power generation is.

The high initial cost, weather dependence, grid connection complexity, weather dependence, rooftop space constraints, battery storage cost and technical expertise. The integration of solar system with the existing electrical grid may require additional equipment and technical expertise to ensure proper power flow and compliance with regulations are required.

The addition of battery storage to a solar system for backup power during outages increases the overall system cost. Proper system design, installation, and maintenance often require specialized knowledge and qualified technicians[13]. The figure 1.3 Summarize the key challenges of renewable energy integration on grid.

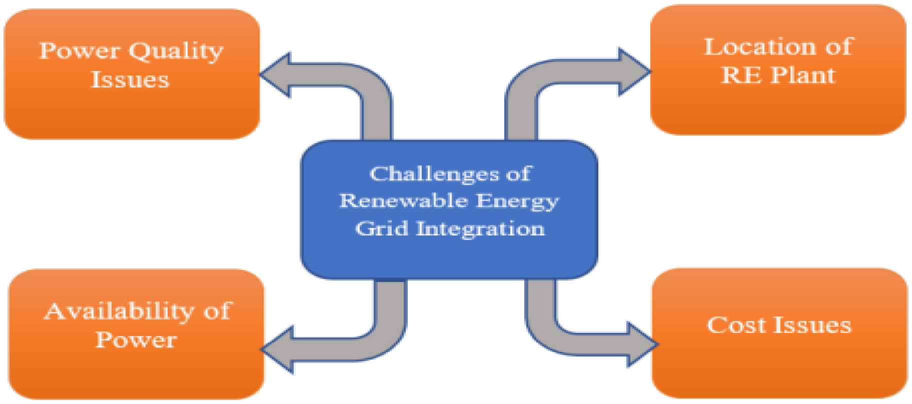


Figure 1. 3:Challenges of Renewable Energy Grid Integration [8].

1.5.3 The Socio-Economic Impacts of SHS

The implementation of SHS has substantial socioeconomic repercussions, especially in rural and underdeveloped communities. SHS can boost access to energy, which promotes economic development, education, healthcare, and general quality of life.

However, the success of SHS integration also depends on factors such as affordability, community acceptance, and the creation of local jobs.

The evaluation of these impacts is essential for a holistic understanding of SHS integration into the power grid. Rural electrification generates substantial and favorable changes in economic welfare and is deemed, by most scholars, a prerequisite for economic growth. The general economic impact is mostly measured in terms of growth of industrial activity, productivity and employment in the rural community[14].

1.6 Problem Statement

Rwanda has made significant strides in expanding electricity access, with a growing focus on renewable energy solutions, particularly Solar Home Systems (SHS). SHS have proven effective in providing off-grid electricity to rural and remote areas, supporting socio-economic development and reducing reliance on fossil fuels. However, the rapid scaling of SHS deployment introduces critical challenges for integration into the national power grid.

The existing grid infrastructure in Rwanda was primarily designed for centralized generation and may not be fully equipped to accommodate a high penetration of distributed solar energy. This can lead to technical issues such as voltage fluctuations, frequency instability, harmonics, and power quality degradation. Furthermore, the intermittent and variable nature of solar generation poses additional challenges for grid stability, load balancing, and overall reliability of electricity supply. Without a comprehensive technical, economic, and regulatory assessment, integrating SHS into the grid risks operational inefficiencies, higher costs, and reduced system reliability.

These challenges may undermine Rwanda’s broader objectives of sustainable energy expansion, rural electrification, and maximizing the contribution of SHS to the national energy mix.

Therefore, there is a pressing need to evaluate the technical feasibility, identify integration barriers, and propose strategies that ensure safe, efficient, and reliable incorporation of SHS into Rwanda’s electricity network.

This project will identify and address the technical barriers, evaluate the impacts on grid stability and reliability, and provide actionable recommendations to ensure that the integration of SHS supports Rwanda's sustainable energy goals while maintaining grid integrity.

1.7 Objective

1.7.1 Main objective

The primary goal of this project is to undertake a detailed technical assessment of the integration of solar home systems (SHS) into Rwanda's national electricity grid. This assessment aims to identify potential technical challenges, evaluate the impacts on grid stability and reliability, and develop strategic recommendations to facilitate the seamless and efficient incorporation of SHS into Rwanda's energy infrastructure, thereby supporting the country's sustainable energy goals and enhancing overall grid performance.

1.7.2 The Specific Objectives

The specific objectives of this project are:

- To design and simulate a system using with SHS (5kwp), inverter and storage batteries that enable smooth integration.
- To evaluate grid compatibility by assessing the ability of Rwanda’s existing power grid infrastructure to integrate Solar Home Systems (SHS), while identifying technical gaps or limitations.
- To identify technical barriers by analyzing challenges associated with SHS-grid integration, such as voltage regulation, frequency management, and power quality issues.
- To assess the impact on grid stability and reliability by examining the effects of SHS integration on load balancing, system performance, and overall reliability, considering the intermittent nature of solar energy.

The objective addresses the need to anticipate and resolve technical challenges that arise during the integration of SHS with the national grid. These barriers may include inverter-grid compatibility, voltage fluctuations, synchronization issues, and system protection coordination. The study identifies these barriers based on literature, field data, and HOMER simulation outputs. Appropriate strategies such as using smart inverters, load balancing, incorporating energy storage, and deploying demand-side management are proposed to ensure technically sound and stable integration process.

1.7.3 The Research Questions

The study will answer the following major research questions:

a. How compatible is Rwanda's existing power grid infrastructure with the integration of Solar Home Systems (SHS)?

b. What are the main technical challenges associated with SHS-grid integration, particularly in terms of voltage regulation, frequency stability, and power quality?

c. What impact does SHS integration have on the stability and reliability of Rwanda's power grid, given the intermittent nature of solar energy??

d. What technological solutions and strategies can effectively mitigate the technical barriers to SHS integration into the national grid?

1.7.4 Justification

Rwanda has made considerable strides toward increasing power access, particularly through the installation of Solar Home Systems (SHS) in rural and isolated areas. These systems have played a critical role in increasing energy access and encouraging sustainability.

Rwanda's existing grid was not designed for large-scale integration of decentralized energy sources like Solar Home Systems (SHS), posing risks of instability and inefficiency without proper assessment. This project addresses the need to ensure SHS integration is technically feasible and sustainable. By identifying and mitigating technical challenges, it supports the development of a more reliable and resilient grid. The results will also inform policy, guide infrastructure investment, and serve as a reference for other countries pursuing similar energy transitions.

1.8 The Scope of the project

This project will focus on conducting a detailed technical assessment of the integration of Solar Home Systems (SHS) into Rwanda's national power grid. It will contribute to Rwanda's long-term energy goals, including achieving universal access to electricity, reducing greenhouse gas emissions, and fostering economic growth through sustainable energy solutions.

1.9 Research Arrangement

The research documenting project will be organized into the following chapter

CHAPTER ONE: This section gives an overview of the project, including its background, problem statement, aims, research questions, and justification. It will provide context for the study by analyzing the significance of Solar Home Systems (SHS) in Rwanda's energy landscape and the need for technical evaluation of their integration into the national power grid.

CHAPTER TWO: This section reviews the available literature on the integration of decentralized renewable energy sources, specifically SHS, into power networks. It discusses key theories, prior research, and case studies from other countries, laying the groundwork for comprehending the technological issues and solutions connected with SHS integration.

CHAPTER THREE: This part outlines the research design and methods used to conduct the technical assessment. It will detail the data collection process, including field studies, stakeholder interviews, and data analysis techniques. The chapter will also describe the mathematical analysis of grid strength, simulation models and tools used to evaluate the impact of SHS on grid stability and reliability.

CHAPTER FOUR: This chapter provides an in-depth analysis of Rwanda's energy sector, examining the current state of the power grid, its design, capacity, and key challenges. It also explores the role of Solar Home Systems (SHS) in the national energy mix, highlighting both their potential benefits and integration challenges. Based on findings from the technical and regulatory assessments, the chapter also presents practical guidelines for SHS integration, including strategies to address technical issues, improve grid stability, and optimize energy management. Policy suggestions to support these initiatives are also discussed.

CHAPTER FIVE: This CHAPTER represent the overall design and simulation. The results were also discussed within these sections.

CHAPTER SIX: This is the final CHAPTER that highlight the important findings and contributions of the study. It will highlight the limitations of the research and offer areas for future inquiry. The chapter will conclude by emphasizing the need for continuous research and policy development to enable the long-term integration of SHS into electricity systems.

CHAPTER TWO: LITERATURE REVIEW AND THEORITICAL BACKGROUND

2.1 Introduction

As the demand for electricity grows and conventional sources of energy deplete, it becomes necessary to incorporate a variety of renewable energy or non-traditional energy source for power generation. Solar energy is considered as one of the most promising sources of renewable energy today [15]. The integration of Solar Home Systems (SHS) into national power grids marks a major change in the energy sector, particularly for developing countries like Rwanda, which aim to expand electricity access while reducing reliance on fossil fuels.

Rwanda has made significant progress in expanding its power grid, but challenges remain, particularly in rural and remote areas where grid coverage is still limited. The integration of solar home systems (SHS) with the existing grid depends on various factors, such as grid capacity, infrastructure quality, and the capability to manage decentralized energy sources[16].

The intermittent nature of solar generation introduces variability that can affect grid reliability, necessitating the development of technological solutions, advanced inverters, battery storage, and smart grid technologies. Additionally, robust regulatory and policy frameworks are crucial to ensure SHS complement, rather than disrupt, existing grid operations[17].

Technological solutions and strategies are essential to mitigate these challenges, such as the use of advanced inverters, battery storage systems, and smart grid technologies that enhance grid flexibility and resilience.

Moreover, the integration process must be supported by robust regulatory and policy frameworks[18].

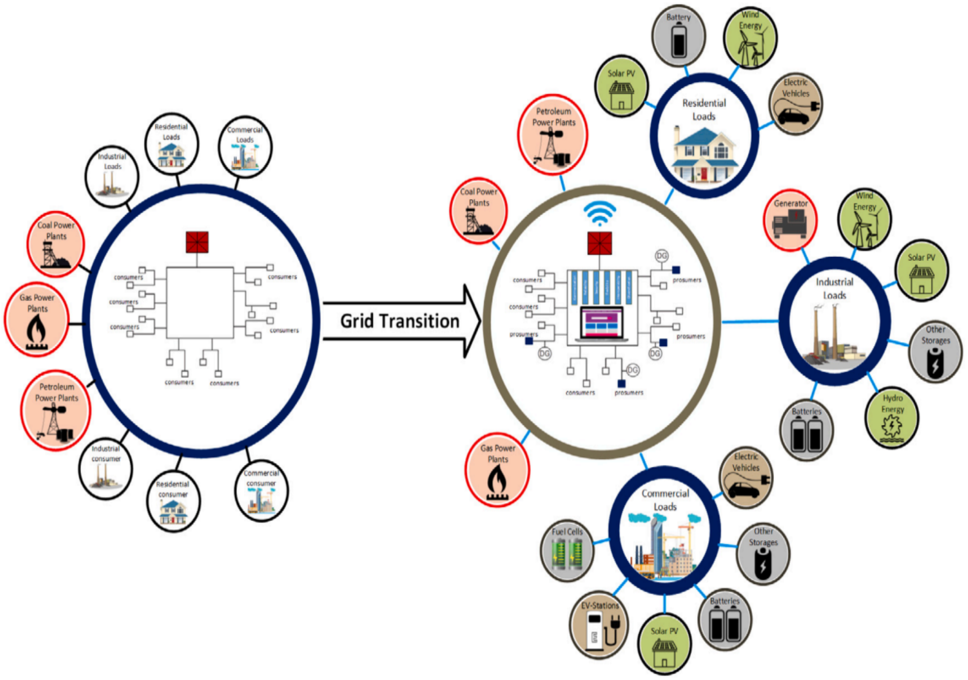


Figure 2. 1:The transition of power grid towards smart grid and distributed generation[12]

Currently, Rwanda has policies in place to promote renewable energy and SHS deployment, but adjustments may be needed to address the specific technical and economic aspects of grid integration, ensuring that SHS can complement and not disrupt grid operations. Developing best practices and guidelines is also critical for facilitating efficient and effective SHS integration[19]. These guidelines should encompass technical standards, grid compatibility criteria, and operational protocols to ensure smooth transitions between off-grid and grid-connected systems. Lessons learned from Rwanda's experience can offer valuable insights for other countries with similar energy profiles and grid infrastructures, providing a model for integrating decentralized energy solutions into national grids to achieve broader electrification goals[20].

2.2 Assessment of Rwanda’s Power Grid Infrastructure

Rwanda has made notable progress in grid expansion, yet rural and remote areas remain under-served. Integrating SHS depends on grid capacity, infrastructure quality, and the ability to manage decentralized energy sources. To become an average middle-income country, Rwanda need some oil and must construct a nominal capacity of 90 GW of solar photovoltaics (PV)[21].

Rwanda's off-grid connectivity has expanded from roughly 0% to more than 10.7%, or 258,670 homes in 2017. This has primarily been accomplished through SHS. The rural electrification Strategy (2016) was a critical factor in the expansion. The RES revised access targets to reflect a greater emphasis on off-grid, and introduced programs to provide systems to low-income homes and stimulate private sector development[16].

2.3 Solar Home Systems (SHS)

The Solar Home Systems (SHS) are decentralized, small-scale energy solutions comprising solar panels, battery storage, charge controllers, and sometimes inverters. Due to their affordability, scalability, and renewable nature, SHS are increasingly recognized as vital for expanding energy access in developing countries. In Rwanda, 18.1% of the population is connected to off-grid technologies like SHS and microgrids. As demand grows, solar PV is increasingly being offered by forward-thinking developers as an energy option for consumers[22]. A solar PV system is simple to use and operates automatically.

It can consume the electricity for free when it is generated; if you do not use all of the electricity produced, the remainder will be automatically transmitted to the electricity grid. Figure 2.2 displays a diagram of typical components of a solar PV system.

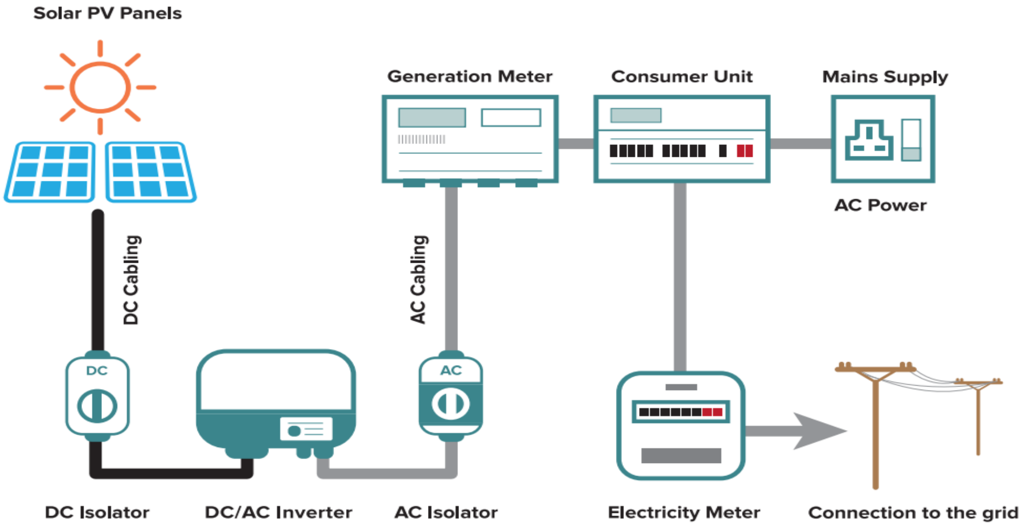


Figure 2. 2:Diagram Configuration showing typical components of a solar PV system [17]

Climate change has necessitated the reduction of carbon emissions. This solar system will create electricity without emitting additional carbon dioxide.

The electricity from the grid can be generated by burning fossil fuels, which emit carbon dioxide and contribute to climate change. The environment benefits from reducing our reliance on energy produced from fossil fuels[23]. The solar home system requires protection since the surplus is injected into the grid; however, for safety reasons, if the grid electricity is taken off, the PV power injected into the grid is instantly turned off. This safety measure protects engineers working on the problem, who could be put at risk if electricity is delivered to the grid during a power outage. When it is safe, the solar PV electricity should be turned back on automatically.

2.4 Charge controller and Energy Storage System (ESS)

2.4.1 Charger controller

A charge controller is a device used in solar power systems to regulate the voltage and current coming from the solar panels to the battery. Its primary function is to prevent overcharging or deep discharge of the battery, ensuring the system operates efficiently and prolongs the battery’s lifespan.

A maximum power point tracker harvests optimum power from the solar module during the bulk charging stage, providing a high charging current until the battery voltage reaches a specified level (tuned for temperature)[24].

2.4.2 The Energy Storage Systems (ESS)

Energy Storage Systems (ESS) serve an important role in integrating renewable energy sources such as SHS into the grid. ESS, particularly battery storage, allows excess energy created during peak sunshine hours to be stored and used when solar generation is low or demand is high. This capacity helps to smooth out the unpredictability of solar electricity, hence improving grid stability and reliability. Understanding the many types, functions, and applications of ESS is essential for designing strategies to support SHS integration[25]. The key components of a grid-connected solar PV system include the SPV array, MPPT controller, DC-DC boost converter, three- or single-phase voltage source inverter, filter, and the grid.

The voltage and current from the array are fed into the MPPT controller, which manages the switching of the DC-DC boost converter to optimize power output. This DC-DC boost converter is also known as an MPPT tracker.

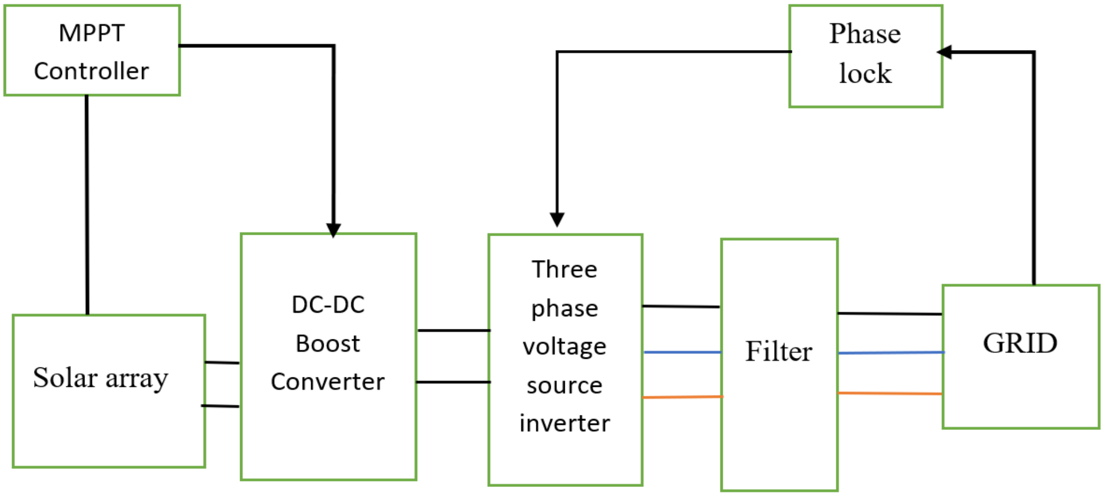


Figure 2. 3:Block diagram of grid-interactive SPV system[15]

2.5 Solar power generation and power grid infrastructure

There are two types of solar power generation utilized in conjunction with grid power: concentrated solar power (CSP) and photovoltaic (PV) power.

The CSP generating, also known as solar thermal power generation, is similar to traditional thermal power generation, which converts thermal energy (steam) into electricity. Unlike solar thermal systems, photovoltaic (PV) solar panels do not rely on the sun's heat to produce thermal power. Instead, they convert sunlight into direct current (DC) electricity through the photovoltaic effect[26]. The DC output is then converted into AC using a single-phase or three-phase voltage source inverter, which is subsequently fed into the grid.

The output of the inverter is not synced with the grid and contains harmonics. As a result, it is synchronized with the grid using a phase lock loop, and a filter is employed to remove the undesired harmonics[27].

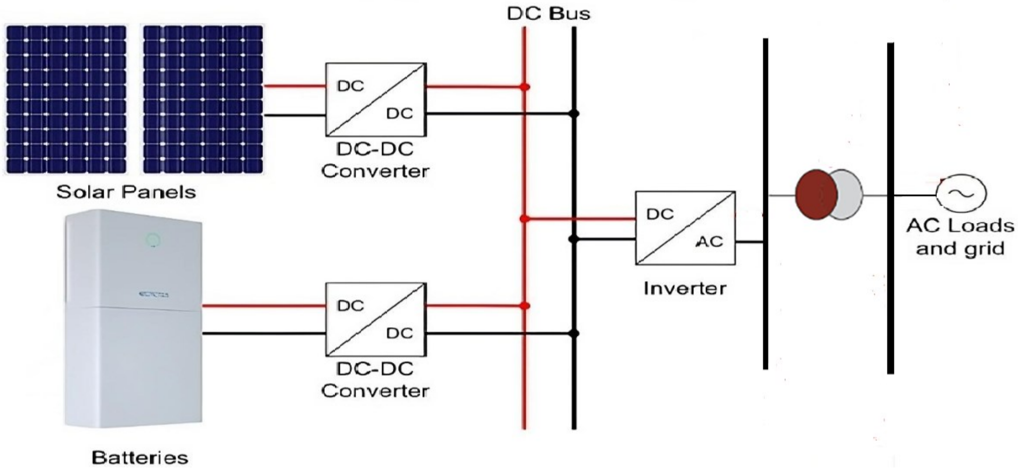


Figure 2. 4:Configuration of PV power station [19]

The power grid, or electrical grid, is a network that delivers electricity from generation sources to end-users, comprising power plants, transmission lines, and distribution systems. It operates by maintaining a balance between electricity supply and demand. Integrating decentralized sources like Solar Home Systems (SHS) introduces variable inputs, requiring the grid to adapt to maintain stability and reliability. Solar panels generate direct current (DC), which is converted to alternating current (AC) via a solar converter and distributed through an AC bus to the grid, battery, or active loads.

A multi-mode inverter manages the battery, serving key roles in energy conversion and system control. First, it converts AC power back to DC for battery charging. Second, it converts the DC energy stored in the battery to AC during discharge[28]. The understanding the structure and function of power grids is critical to evaluating the challenges and opportunities of SHS integration.

2.6 PV systems grid integration challenges

2.6.1 Stability and reliability

Grid stability refers to a power grid's capacity to maintain a constant voltage and frequency despite fluctuations in electricity supply and consumption. In contrast, reliability refers to the grid's ability to provide uninterrupted power. Thorough study on improving PV cell efficiency, lowering PV panel costs, and extracting the most power from systems paves the path for significant expansion in PV power generation[29].

Furthermore, clean and environmentally friendly energy sources like solar power play a key role in reducing greenhouse gas emissions by decreasing reliance on fossil fuels while meeting essential load demands. However, their variable generation, along with technical and protection-related challenges, can hinder the efficiency, reliability, and safety of photovoltaic (PV) integration into the power grid[30]. Grid-connected distributed systems have gained popularity as they can supply power directly to consumers or feed into the utility grid. PV systems can be installed on commercial or public buildings, allowing for various system sizes. In contrast, grid-connected centralized systems are typically large-scale, ground-mounted power plants that generate electricity exclusively for the utility grid, often with power ratings exceeding the kilowatt range[31].

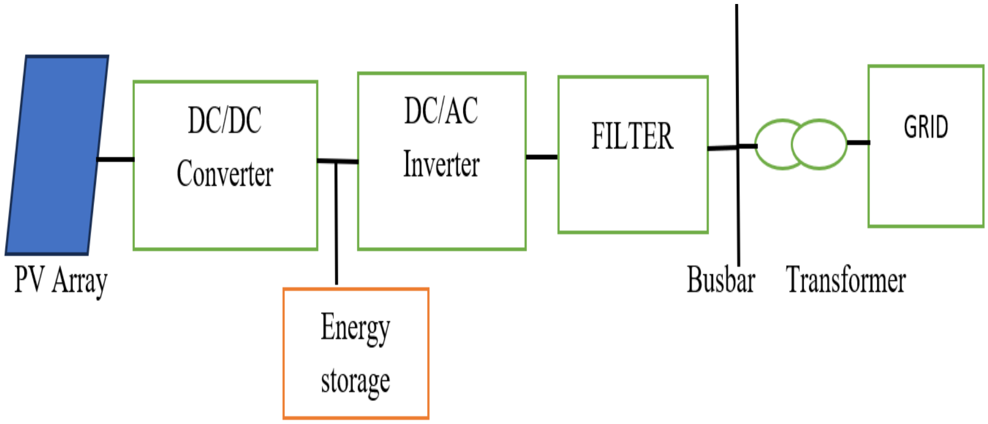


Figure 2. 5:Components of a grid connected PV systems[32]

The Figure 2:5 shows the usual setup of a PV system. The PV array converts solar energy into a specific DC current and voltage based on the number of modules. If the inverter requires a higher voltage, a DC/DC boost converter is used. Energy storage devices can also be incorporated to store the generated energy for use when the grid connection is unavailable. A three-phase inverter converts power and distributes it to the grid. The filter reduces the high frequency harmonics that emerge when power semiconductors switch[33].

2.6.2 The Voltage Regulation and Frequency Control

The voltage regulation and frequency control are crucial components of grid management. Voltage control keeps the electrical voltage within a specific range, limiting damage to equipment and guaranteeing effective power supply. Frequency control maintains the grid's frequency, which is commonly 50 or 60 Hz, which is required for electrical devices to function properly. The integration of SHS can upset these parameters, especially if the systems are not correctly synchronized with the grid, necessitating complex control methods and technologies. To provide load frequency control (LFC) of the power system with integration of solar PV, the system uses the creation of a proportional integral derivative (PID) scheme and filters[34].

2.7 Smart grid

The smart grid enhances traditional electrical grids by using digital communication technologies to efficiently monitor and manage electricity flow. It facilitates the integration of renewable energy sources, including Solar Home Systems (SHS), through real-time data collection, demand response, and automated regulation. These capabilities address the challenges of incorporating variable and distributed energy into the grid. Globally, smart grids are being adopted to increase electricity supply from renewables like geothermal, hydro, solar, and wind, as seen in Indonesia's efforts to reduce fossil fuel dependence and electricity subsidies amid rising demand.

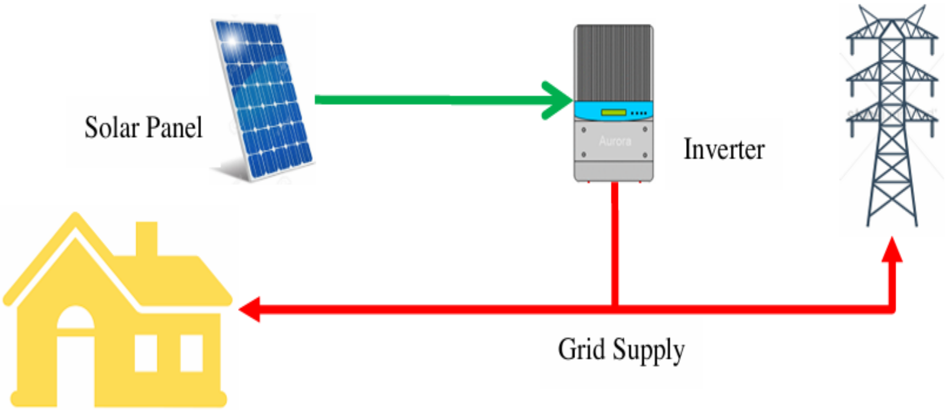


Figure 2. 6:Smart Home Micro Grid Architecture [35]

The smart grid technology, which incorporates advanced hardware and software components, enables utilities to improve grid management and gives consumers more control over their energy consumption. Building a sustainable, adaptive, and dependable infrastructure is critical for meeting energy demands. In contrast to traditional grids, smart grids can automatically adjust energy supply and demand using real-time data collected from smart meters, sensors, and other Internet of Things (IoT) devices.

This real-time data enables grid operators to forecast energy demand and supply, monitor the grid's condition, and take proactive measures to prevent power outages, minimize energy waste, and enhance the grid's overall efficiency[36].

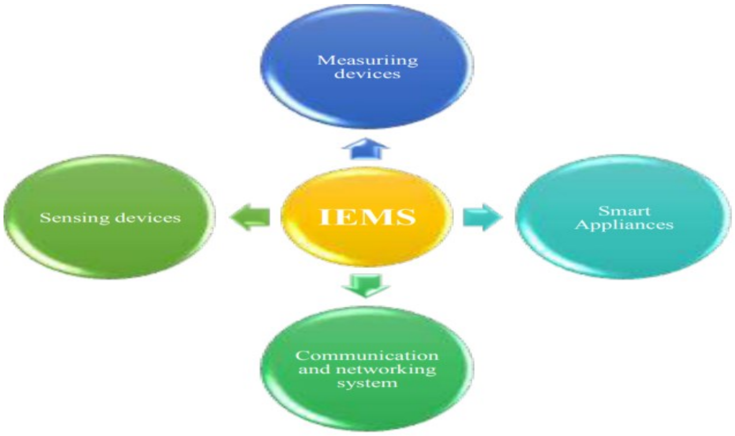


Figure 2. 7:Intelligent Energy Management Systems (IEMS) [27]

The IEMS collects data from many sources integrated into a smart grid, then uses machine learning algorithms to analyze it and make informed decisions targeted at maintaining the best balance of energy demand and supply. Machine learning algorithms are key elements of intelligent Energy Management Systems (EMSs). They can analyze historical data, predict future energy consumption, and make optimal decisions based on the current grid conditions[37].

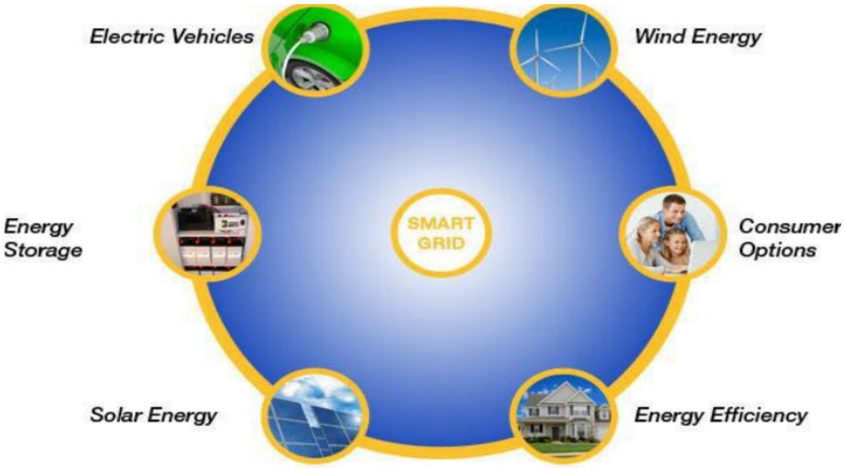


Figure 2. 8:Smart grid features[38]

2.8 Similar Works

In [15], The authors discuss the integration of solar power into the electrical grid reveals that electricity demand is steadily rising, while conventional energy sources are being depleted. As a result, incorporating various renewable or alternative energy sources into power generation has become essential. Solar energy is one of the most promising renewable energy sources today. As conventional energy sources deplete, solar photovoltaic technology can be used to pool their output and feed it into the main utility grid. A major drawback of the SPV system is its low reliability, as it is an intermittent energy source that is available only periodically and unpredictably.

However, this limitation can be mitigated by integrating solar power with the main grid, allowing electricity to be supplied from the grid during nighttime or periods of low sunlight, ensuring high reliability and efficiency, and batteries can be incorporated into a stand-alone SPV system to achieve the same result.

The authors [35]**,** The incorporation of solar energy into the smart home microgrid was explored to enhance energy efficiency and environmental sustainability. The key insights highlight that energy supply is a critical global challenge due to increasing demand and the depletion of essential resources for energy production. Strategic initiatives have been taken, such as using non-fossil power plants or renewable energy (solar cells, wind, water, etc.) as a substitute for fossil fuels.

The development and utilization of renewable energy sources necessitate a lengthy process, as well as support for fossil energy sources, in order to promote energy integration. The Smart grid is a modern electricity network infrastructure that can integrate alternative (nuclear, geothermal) and renewable energy sources (wind, water, air, diesel, etc.), as well as improve reliability, efficiency, and security through automatic control and the use of modern communication technology.

The paper [39] , the paper examines the planning of photovoltaic (PV) solar power plants as a future alternative energy source in Indonesia. The authors explore an energy management system designed to regulate and coordinate the energy supply process by analyzing electrical data from smart meters and data concentrators. This system enables monitoring and management by scheduling electricity usage from solar energy.

Recent advancements in switching converter technology have significantly enhanced the utilization of nonconventional energy sources as decentralized power generators.

In [40] , the authors works on A review of PV system integration into the electrical grid highlights the growing interest among research groups in adopting renewable energy due to rising electricity consumption, fossil fuel depletion, and environmental impacts. The study explores PV generation integration methods, the advantages of connecting PV systems to the grid, key features for seamless integration, and the challenges and potential solutions. Additionally, feasibility data on PV grid integration is presented for academic researchers. Finally, the authors examine the challenges that remain in the integration of PV systems into the electric grid, which include technological issues, power quality concerns, insurance issues, and innovation and development issues. The gaps identified within the above literature will be resolved in this project work.

2.9 Technical Analysis of SHS and Grid Compatibility

The Electricity demand can be fulfilled in a variety of ways, and incorporating renewable energy sources can be a dependable, environmentally friendly, and cost-effective solution. Energy requirements in remote and isolated places not directly supplied by the electrical grid are best satisfied by hybrid systems employing multiple renewable energy sources[41].To determine the technical feasibility of integrating SHS into the national grid. The following procedures are conducted:

i. **Simulation and Modeling:** Perform simulations using power system analysis software (e.g., HOMER and MATLAB) to model different integration scenarios and assess the impact on grid stability.

ii. **Component Analysis:** Evaluate the technical specifications of SHS components, such as inverters, batteries, and controllers, to ensure compatibility with grid requirements.

iii. **Performance Testing:** Test SHS performance under grid-connected and off-grid conditions, focusing on power output, reliability, and safety.

iv. **Impact Assessment:** Identify potential technical challenges such as harmonics, power factor issues, and load management, and propose mitigation strategies.

2.10 Growth and Adoption of SHS in Eastern Africa

In recent years, the integration of Solar Home Systems (SHS) has emerged as a promising solution to the persistent energy access challenges in Eastern Africa. Countries such as Kenya, Tanzania, and Uganda have seen significant growth in SHS deployment, driven by falling solar panel prices, innovative financing models (such as pay-as-you-go systems), and supportive government policies[42]. These systems have proven particularly effective in rural and off-grid areas, where grid expansion is economically unfeasible. The decentralized nature of SHS allows households to access electricity for lighting, phone charging, and small appliances, contributing to improved living standards and economic productivity [43].

Despite their benefits, the integration of SHS in Eastern Africa faces several challenges. Affordability remains a major barrier, especially among low-income households, even with financing options like microloans and pay-as-you-go schemes [44]. Technical issues, such as battery degradation and lack of maintenance services, also affect long-term performance.

Furthermore, policy and regulatory frameworks in some countries are not yet fully aligned to support off-grid energy solutions at scale. Nonetheless, with ongoing innovations in technology and business models, as well as growing international interest in sustainable energy access, SHS is expected to play a pivotal role in the region's future energy landscape[45].

2.11 Research gaps

Existing literature provides valuable insights into solar PV integration, smart grids, and energy management. However, most studies are either generalized or focused on international contexts, with limited attention to the specific technical, regulatory, and policy conditions in Rwanda.

Importantly, there is a lack of comprehensive studies combining technical simulations, grid stability assessment, and policy evaluation for decentralized SHS integration. The overall gaps are summarized in table 2.1

Table 2. 1:Summary of Identified Gaps

SN	Areas	Gaps Identified
1.	Grid stability & reliability	Limited Rwanda-specific studies on voltage, frequency, harmonics with SHS integration.
2.	Technical solutions	Few studies on inverter settings, ESS, and mitigation strategies in high-penetration scenarios.
3.	Policy & regulation	Lack of research linking grid feasibility to supportive policies and incentives.
4.	Smart grid	Minimal studies on integrating SHS into Rwanda's emerging smart grid infrastructure.
5.	Best practices & guidelines	No comprehensive framework combining technical, operational, and policy aspects.

CHAPTER THREE: METHODOLOGY

3.1. Introduction

This study aims to evaluate the technical feasibility, challenges, and opportunities of integrating Solar Home Systems (SHS) into Rwanda's national power grid. The methodology combines technical simulations, component and system analysis, and policy assessment to provide a holistic understanding of SHS-grid integration. The approach ensures that findings are actionable and linked to recommendations for policymakers, utilities, and SHS developers. This methodology outlines the steps and processes for conducting a technical assessment of Solar Home System (SHS) integration into the power grid in Rwanda. The approach combines quantitative and qualitative methods to evaluate the technical, economic, regulatory, and stakeholder aspects of SHS-grid integration.

3.2 Research design and Steps

The research adopts a mixed-method approach, combining quantitative simulations with qualitative policy and regulatory analysis. For quantitative Analysis, the assessment of grid stability, power quality, and operational performance using simulation software has been performed.

Apart for Qualitative Analysis, the review of national policies, regulations, and best practices for integrating decentralized solar energy into existing grids will be also performed. This approach ensures that technical, economic, and policy aspects of SHS integration are comprehensively addressed. There are many steps in the research process involves several key steps, including problem identification, literature review, hypothesis formulation, research design, defining the target population, data collection, data analysis, and report writing.

Within this project work, the steps in figure 3.1 are followed to accomplish this task.

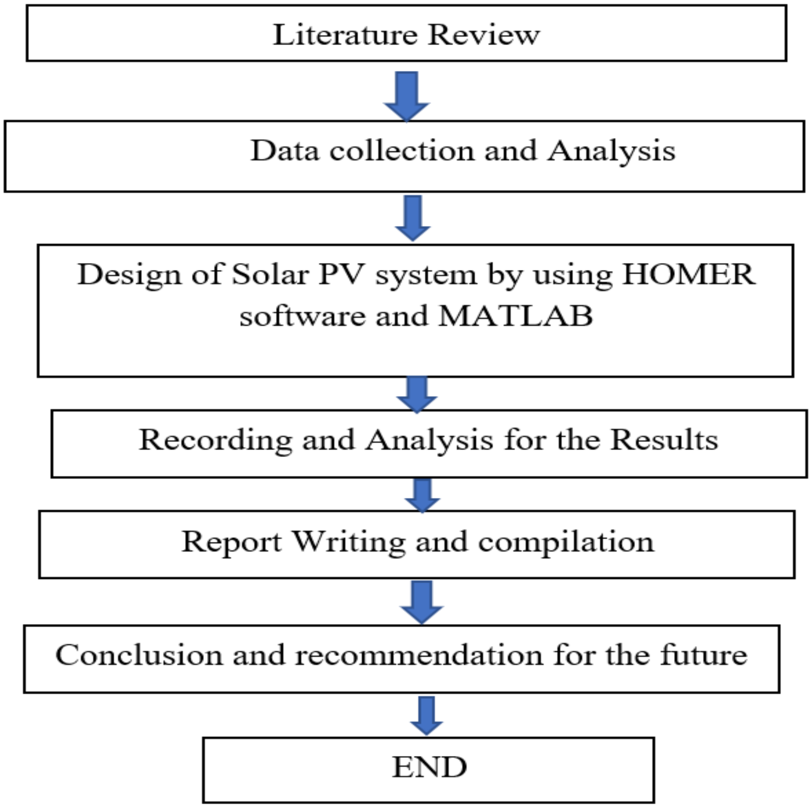


Figure 3. 1: Research steps

3.2.1. Selection of Study Case Data

This study focuses on the integration of Solar Home Systems (SHS) into the national grid across all districts of Rwanda, excluding the City of Kigali. The selection was guided by the following criteria:

1.Targeting Rural and Peri-Urban Areas where the City of Kigali, being fully urbanized and well-served by the national grid, was excluded to allow the study to concentrate on areas where SHS have been widely deployed due to limited or no grid access.

2.Widespread SHS deployment as he rural and peri-urban districts of Rwanda have seen a significant adoption of SHS technologies, primarily through government programs (e.g., Rwanda Energy Access

Results-Based Financing) and private solar companies. These areas present an ideal environment for studying SHS-grid integration feasibility.

The study uses a dataset that includes system capacities per district, Number of installed SHS units, Geographic and demographic distribution, Solar resource availability, Estimated load demand and consumption behaviors

3.3. Data collection

The Data on Solar Home Systems (SHS) installed in Rwanda were obtained from the Rwanda Energy Group, detailing the number of households using SHS and their system capacities in kilowatts. A comprehensive literature review was conducted on SHS, grid integration, and Rwanda's energy sector, including analysis of the national electrification plan and relevant energy policies. Additionally, case studies from other countries with SHS grid integration were reviewed to identify best practices and challenges. These data and analyses provided valuable insights into real-world integration scenarios and challenges in Rwanda. The information gathered from diverse sources using various instruments and approaches often includes numerical numbers, ratings, and descriptive narrations of the solar system in Rwanda with the following goals:

i. **Adoption Patterns**: Understanding the demographic, geographic, and socio-economic factors influencing SHS adoption.

ii. **System Performance**: Measuring metrics like energy output, capacity utilization, and efficiency.

iii. **Impact Assessment**: Evaluating the socio-economic and environmental benefits, such as reduced energy costs, improved education outcomes, and decreased carbon emissions.

The SHS data were analyzed with a focus on capacity, location, and system architecture in comparison to existing grid-integrated SHS. Records including solar home capacity, system ID, company, and installed capacity across different districts in Rwanda are detailed in Chapter Four. The SHS data architecture typically monitors key parameters such as solar panel output (kW) and load consumption (Wh) to ensure optimal performance. However, obtaining data on battery charge status (Ah, voltage) and system health indicators was challenging, limiting insight into battery efficiency and potential system faults or degradation.

The systems can be classified as smaller or larger in terms of capacity based on power generation and residential energy consumption.

A typical SHS in Rwanda could have capacity ranging from 6.3W to 5000W. Data relating to these capacities would include power output, battery utilization, and load consumption.

3.4. Current SHS Architecture in Rwanda (Off-Grid Systems)

They are decentralized Stand-Alone Power Systems: These systems are generally standalone, with no interconnection to the national grid. They operate independently and are used in areas that lack access to electricity. For stand-alone power systems, the SHS typically includes solar panels, charge controllers, batteries, and few with inverters, they are located in area with no access to electricity to provide power to the household.

3.5. Grid-Integrated SHS Architecture

Grid-integrated SHS refers to systems that are either partially connected to the grid or completely connected. The Grid-Integrated SHS are systems that can supply power to the grid after to fulfill the household's energy demands.

The bidirectional energy flow systems are used to export excess solar into the grid when generation exceeds the home use. This can help to improve the overall grid stability and contribute to reducing energy deficits in rural areas. As comparison the architecture of grid-integrated SHS represents a more modern, efficient, and scalable approach compared to the current off-grid systems. The key differences with current Solar Home System lie in the advanced data collection and monitoring capabilities, the ability to export energy to the grid, and the enhanced management of energy resources through smart systems. The entire system is provided on figure3.2 as below:

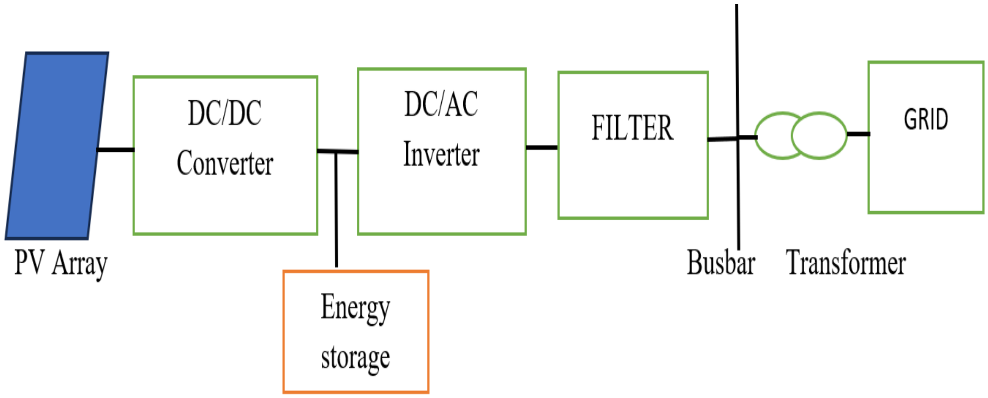


Figure 3. 2: Grid-integrated SHS Architecture

CHAPTER FOUR: GRID STRENGTH ANALYSIS, DESIGN AND SIMULATION

4.1 Data Analysis

The data from different site in Rwanda are the solar generation capacities within different district of Rwanda. According to the Rwanda Energy Group report, the total installed capacity of solar power plants connected to the national grid is 12.050 MW. There are from three solar farm: the Jali solar farm located in Kigali city, Gasabo District with the total installed capacity of 0.25 MWp; Gigawatt Global located in East, Rwamagana District with 8.5 MW capacity and Nasho Solar power plant located in East, Kirehe District with 3,3 MW. However, 7,356,420Wp in terms of capacity are available as off-grid in various districts of Rwanda as shown bellow

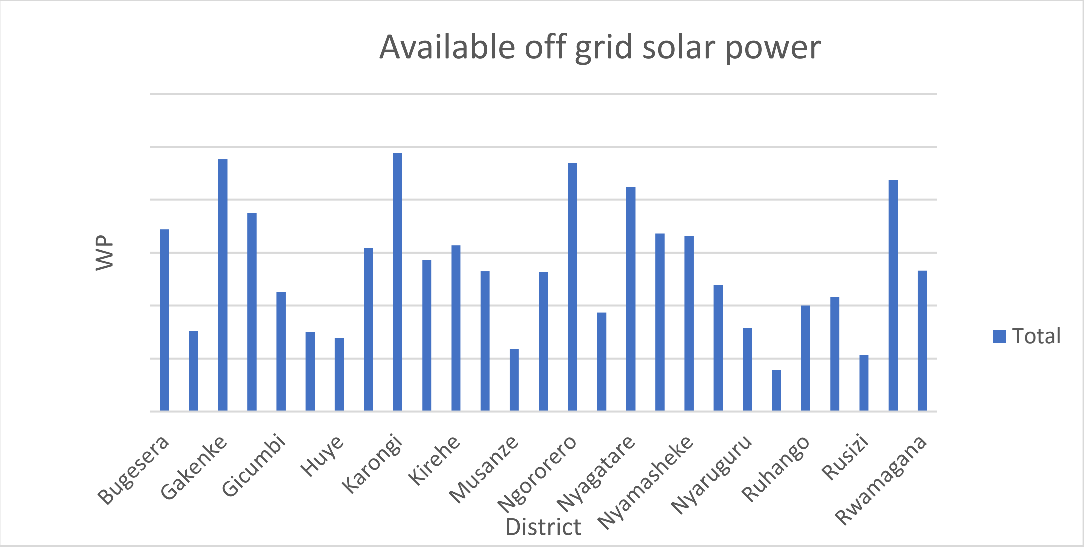


Figure 4. 1:Available off grid solar power by district

The Rwandan government aims to increase the number of solar power plants, reduce production costs, and optimize the utilization of the country's renewable energy resources. The approximated installed solar home system is show on Figure 4.3 and table 4.1. The table 4.1 describes the current solar home system size in Rwanda within district of Rwanda.

Table 4. 1:Total system size available in each district

District	Solar Home System Capacity										
	6.3	**7.8**	**10**	**12**	**15**	**16**	**20**	**30**	**50**	**120**	**5000**
Bugesera	186	362	7537	8828	3422		5316		21		
Burera	1188	7519	1199	360	548		2700	258	1		
Gakenke	3375	2953	8048	5139	10976		5349	497	73		3
Gatsibo	1212	2542	7331	10565	715		6671	5	60	1	1
Gicumbi	3050	3282	3997	5148	150		3530	148	37		3
Gisagara	2012		5026	823	878		3054		74	1	
Huye	1876	365	3737	3174	548	348	1645		32		
Kamonyi	724		3380	3685	10499		3412		8		1
Karongi	1621	1568	3711	3096	8783		12801		78		8
Kayonza	1409	2415	6625	5066	1547		5367		11		
Kirehe	1667	2501	7675	6417	2353		3861	530	30		
Muhanga	4336	25	1455	2092	8049	504	3383		28		6
Musanze	159	2578	1357	337	3424		1313	62			
Ngoma	820	4933	3018	5865	1189		4163	538	34	6	
Ngororero	2688	4909	6170	5279	2115		12815		15		1
Nyabihu	326	2047	3733	3925	51		3701	297	14		1
Nyagatare	1408	5392	8916	10292	2228		6210	6	47	2	3
Nyamagabe	4817	53	5007	5673	738		8329	271	27		2
Nyamasheke	3712	4597	2583	1416			10880	147	151		1
Nyanza	627	1171	4728	6225	33	3760	2088		31		
Nyaruguru	3223	40	2494	429	208		5072		42		1
Rubavu	561	662	2477	940	469		1274	23	4		
Ruhango	678	1463	2794	5135	1104	1387	2755		20		
Rulindo	4340	4585	1105	6829	246		2749		25		1
Rusizi	1250	875	3060	933	860		1884		7		
Rutsiro	1204	4541	3456	2419	15143		5120	4	32		
Rwamagana	3375	2001	4316	5244	3285		3671		11		
TOTAL	51844	63379	114935	115334	79561	5999	129113	2786	913	10	32

The system size installed as the table 4.1 highlights; the different sizes of Solar Home System installed in Rwanda.

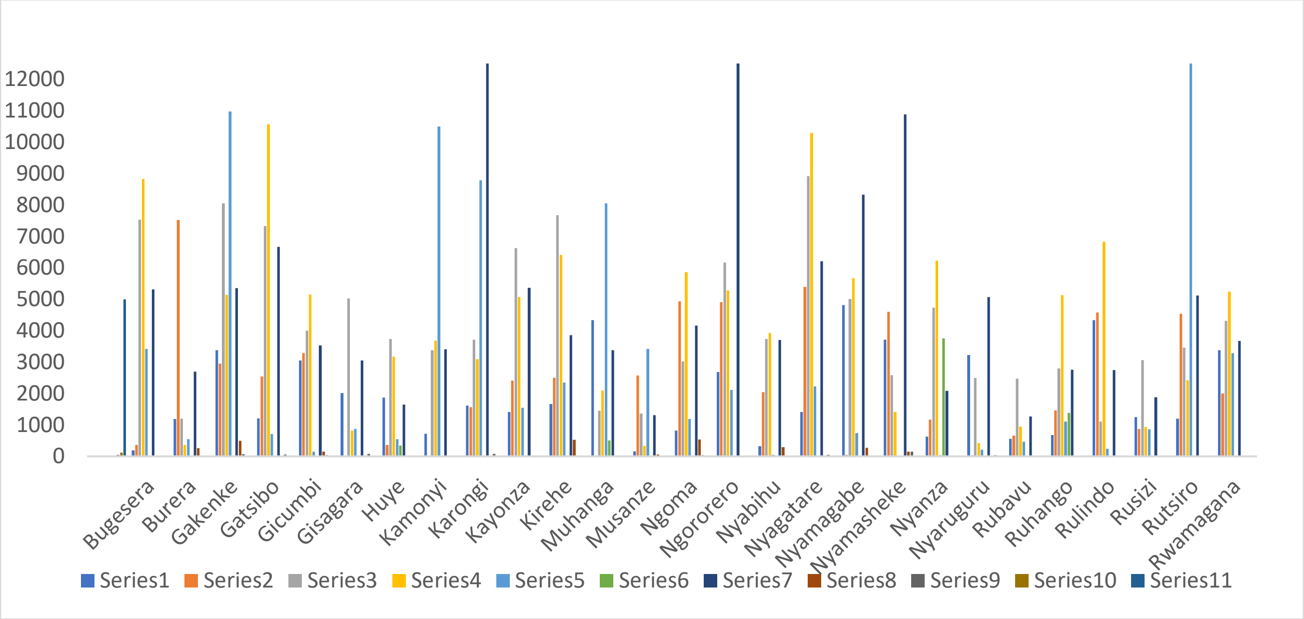


Figure 4. 2:Installed solar home system per capacity

The actual information show that Rwanda has a lot of potential for solar energy, with around 4.5 kWh/sqm and a peak sun hour of 5. According to data taken on site five hundred sixty-three thousand eight hundred seventy-four (563874) households are using solar system with different supply in Rwanda.

4.1.1 Standard of Solar Home Systems

The size of a solar panel is determined by the number of cells it contains. The most common sizes are 60-cell and 72-cell panels. Typically, 60-cell panels, which measure about 5.5 feet by 3 feet and weigh around 40 pounds, are the standard choice for residential installations. In contrast, 72-cell panels are larger, measuring approximately 6.5 feet by 3 feet and weighing about 50 pounds, making them more suitable for commercial use. A typical solar panel system consists of 15 to 19 panels, covering an area of 260 to 340 square feet. However, factors such as efficiency, power output, warranty, and brand reputation are more crucial than panel size when selecting a solar system.

4.1.2 Solar panel efficiency

Solar panel efficiency represents the percentage of sunlight that hits the panel's surface and is converted into usable electricity. Contemporary solar panels typically have efficiency levels between 17% and 22.8%, with premium models achieving the higher end of this range. Panels with higher efficiency require less space, allowing for the installation of more panels on a given rooftop.

4.1.3 The Solar panel warranties

There are two types of warranties for solar panels. The first is the product warranty, which covers the replacement of a panel by the manufacturer in case of defects. While a 12-year product warranty is standard, more brands are now offering 25-year coverage. The second type is the performance warranty, which ensures that the panel maintains a certain level of energy output throughout its lifespan. Most well-known panels include a 25-year performance warranty, though their efficiency gradually decreases over time from installation to the 25-year mark.[46].

4.1.4 How to select best solar panel

The simplest approach to determine the appropriate solar panel size that can supply the sufficient energy for the home usage is through solar system contractors. Solar contractors design your system based on your energy needs, available roof space, and local sunlight conditions. They can suggest a system size that fits your roof while helping to reduce or eliminate your electricity costs[46].

This can benefit users by lowering electricity bills by generating renewable electricity, increasing the efficiency and value of their homes, reducing their reliance on fossil fuel-generated electricity, and helping the environment by lowering their greenhouse gas emissions.

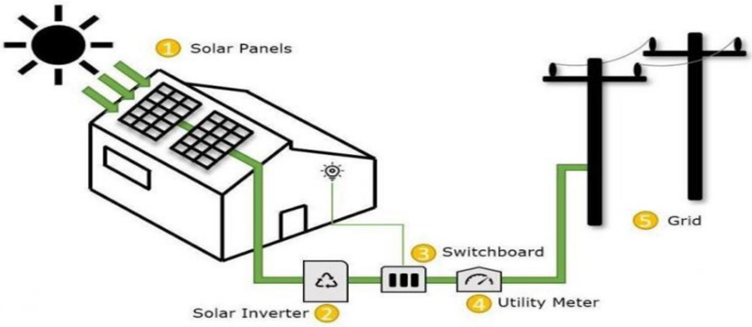


Figure 4. 3: Proposed Solar PV arrangement including inverter and battery [35]

There are various ways to mount solar systems to a roof structure. For Solar Ready homes, technicians must select the appropriate attachment method based on the system's specifications and the roof's design capacity. To ensure the roof can support the additional load of standard solar systems, builders can consult local building code authorities[47].

4.2 Quality Standards for Solar Home Systems and Rural Health Power Supply

In recent decades, the importance of internationally recognized standards in electrical engineering has grown due to increased international trade, shorter product life, and global spread of production locations and consumers. The worldwide Electrotechnical Commission (IEC) primarily pursues worldwide standardization initiatives in photovoltaics, which are then approved by national and regional agencies[48].

Table 4. 2:List of Existing Standards [37]

Standard	Number amens	Status Equival	Descriptions	Component	Application
IEC	61215	04/93 DIN EN	Crystallin silicon terrestrial photovoltaic (PV)module Design qualification and type approval	PV-Mod	Type test
DIN	40025	05/97	Specification sheet and nameplate details for photovoltaic (PV) module type test units	PV-MOD	Type test
IEC	61646	11/96	Thin-film terrestrial PV modules: Design qualification and type approval	PV-Mod	Type test
IEC	60891	04/87 DIN EN	Temperature and irradiance modifications to observed I-V parameters of crystalline silicon PV systems.	PV-Mod	Type test
IEC	60335-1	06/91 DIN EN	Safety standards for household and similar electrical appliances, Part 1: General requirements (3RD edition).	LR	Type test
SABS	0142		Code of Practice for the wiring of Premises	Syst	Installation
IEC	60998-25	01/96	Connection devices for low-voltage circuits used in domestic and similar applications, including terminal boxes or connection devices.	Syst	Installation

The consumer-facing details include the PV power rating on the package, a note about battery replacement, and precise voltage and current specifications for the ports that are compatible with products being charged or powered. The user manual provides instructions on the placement, orientation, and connection of the PV module, how to establish permanent and appliance connections, how to assess the battery's state of charge, and the specifications and replacement methods for the components (during and after warranty period).

In terms of warranty, accurately specified and consumer-facing, minimum of two years for the main control unit, battery, and PV module, and minimum of one year for the accompanying appliance[49].

The table 3.2 describe the specific standards that are currently adopted in Rwanda.

Table 4. 3: Specific standards for Solar home system in Rwanda [40]

SN	Corresponding Equipment	Standard (Test method and Minimum requirements)
1	Quality requirements for equipment's less than 350w	RS IEC/TS62257-9-5 or RS IEC/TS62257-9-8
2	Components based solar home system	RS IEC60986 and RS IEC61056(Lead acid Batteries, RS IEC 61215(PV Module), RS IEC/TS 62257-12-1(Lamps), RS IEC 61960, RS IEC62133-2(Lithium batteries), RS IEC62509(For charge controllers), RS IEC62109-1 and RS IEC62109-2(PV Inverters Reliabilities Test), RS IEC 62124(Standalone system Design verification).

4.3 Architecture of Solar Home Systems

The Rwanda, with its vast rural areas and limited grid infrastructure, is increasingly adopting Solar Home Systems (SHS) to meet the energy needs of off-grid communities. SHS are small-scale, decentralized solar power solutions designed to provide electricity to homes outside the national grid. The architecture of SHS in Rwanda has evolved to prioritize affordability, accessibility, and efficiency in rural energy supply. Additionally, solar architecture designing buildings to harness solar energy through features like solar panels promotes sustainability and energy efficiency, offering a viable approach to addressing climate change. By incorporating these green practices in design, architects can help address the climate crisis head-on[50].

The quality of architectural integration is determined by the effective and harmonious incorporation of solar collectors, addressing functional, structural, and aesthetic aspects. When integrated into building elements like roof coverings, façade cladding, sun shading, or balcony fencing, the solar system must fully perform the functions and meet the requirements of the components it replaces[51].

Rwanda's government, in collaboration with international organizations and private sector companies, has been actively working on increasing the adoption of SHS to reduce energy poverty and improve the quality of life for Rwandans[52].

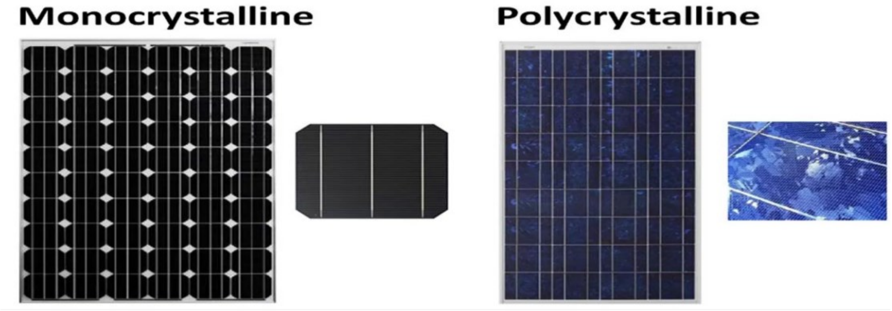


Figure 4. 4:Monocrystalline, thin film and polycrystalline [40]

Monocrystalline solar cells are the most efficient at converting solar energy into electricity. Polycrystalline cells are slightly less efficient but more affordable to manufacture. Amorphous (thin-film) solar cells are less than half as efficient as the top-performing cells, but they are the least expensive to produce [7].

The table 4.4 Comparing Monocrystalline and Polycrystalline Panels provide the key comparison summary between those types of solar panels.

Table 4. 4:Comparing Monocrystalline and Polycrystalline Panels [41]

Features	**Monocrystalline**	**Polycrystalline**
Efficiency	Higher (15-22%)	Moderate (13-16%)
Cost	More expensive	More affordable
Performance	Better in low-light conditions	Good but less efficient in heat
Durability	Longer lifespan	Durable but slightly less robust

The ratio of solar PV supply to power grid supply varies according to the size of the solar PV system. When the solar PV supply exceeds the building's demand, the extra electricity will be exported to the grid.

When there is no sunlight to create PV electricity at night, the power grid will meet the entire building's demand. A grid-connected system can effectively minimize your dependence on utility power, increase renewable energy generation, and benefit the environment[53]. The proposed system will appear as in figure 4.5

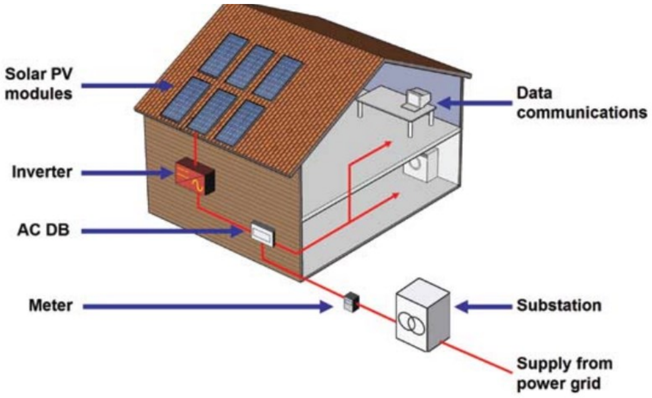


Figure 4. 5:Integrating Solar PV system configuration [42]

The architecture of Solar Home Systems in Rwanda is critical to meeting the country's energy goals, especially in rural areas without access to the national electricity grid.

Rwanda is making progress toward universal access to power, minimizing environmental impact, and increasing inhabitants' quality of life by harnessing solar technologies. However, issues remain, including as pricing, battery disposal, and technician training. Continued investment in SHS infrastructure and policy support will be critical to the achievement of Rwanda's renewable energy strategy[54].

4.4 Architecture comparison of the current SHS already installed with proposed system

The current Solar Home Systems typically consist of photovoltaic (PV) panels, batteries for energy storage, wiring and load. SHS systems are typically designed to power basic household appliances such as LED lights, small fans, radios, and mobile phones.

Some systems are scalable, allowing for the addition of more panels and batteries to support additional loads such as refrigerators or TVs[55].A charge controller, inverter, and distribution system are necessary to supply AC power to household appliances and distribute electricity within the home. Due to the low power rating of individual PV modules, they are typically connected in a hybrid series-parallel configuration to enhance performance based on the application. In a centralized PV system architecture, multiple subsystems are connected to a single converter and managed by a centralized controller. The table 4.5 summarize the comparison of proposed system with existing one.

Table 4. 5:Comparison of existing solar home system and proposed ones

Existing solar home system architectures	**Proposed grid connects solar home system architectures**
Panel	PV
Batteries and wires	Charge controller, converter, Batteries and MPPT
Load	Load and grid

4.6. Grid Strength Analysis of Rwanda Network

Normally, the rising number of grids coupled with photovoltaic (PV) inverters caused concerns with the utility grid's stability and safety, as well as power quality issues. Grid-connected PV systems account for about 92% of the total installed PV capacity. Thyristor-based central inverters connected to the utility grid were first introduced to the market in the mid-1980s. In the 1990s, SMA developed the first transistor-based inverter.

Figure 4.6 Briefly depicts the evolution of grid-connected PV systems and off-grid systems up to the year 2010[31].

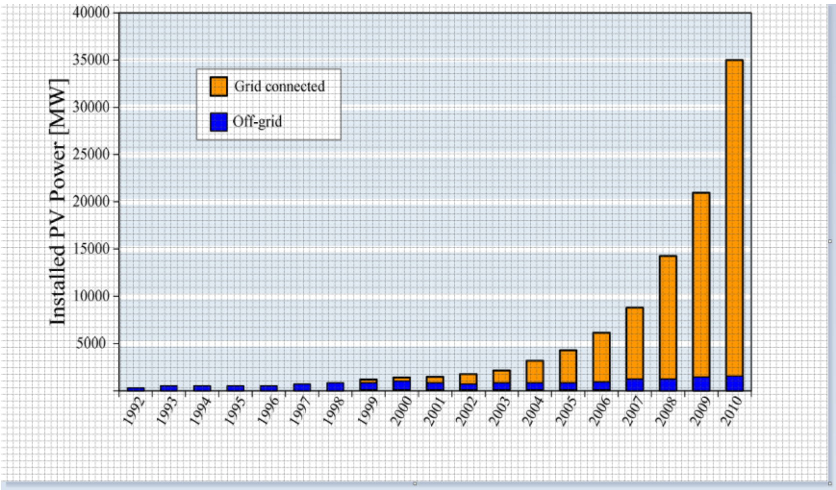


Figure 4. 6:Cumulative installed grid connected and off-grid PV power in the reporting countries between 1992-20010[31].

Since 1999, there has been some shift in off-grid development, whereas grid-connected systems have seen significant growth since 2006. The International Energy Agency (IEA) categorizes photovoltaic (PV) systems as either off-grid or grid-connected. In this study, a pyranometer measured solar irradiance levels ranging from 0 to 1600 W/m² for the grid-connected system. A Siemens Logo Comfort PLC program was employed to simulate sensor outputs and control switching operations.PVsyst software was utilized to design, model, and evaluate both the technical and economic performance of the system[56].

The Rwandan government understands the critical role that electricity availability plays in speeding economic growth by boosting health and living conditions. Energy, particularly access to electricity, is the Government's top priority. Expanding access to energy requires collaboration among power sector stakeholders to connect new customers and drive economic development.

In Rwanda, the grid-connected distribution network includes substations, medium-voltage (MV) primary feeders, distribution transformers (DTs), low-voltage (LV) distributors, and service mains, all working together to deliver electricity to end-users)[19].

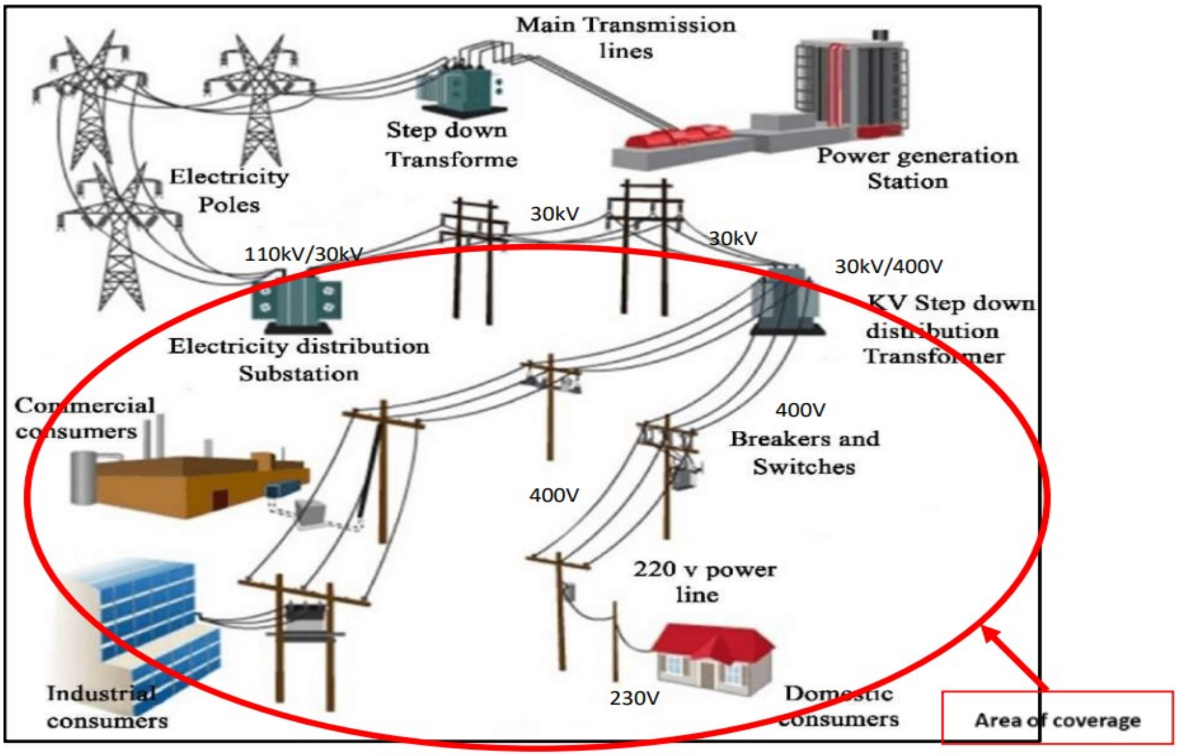


Figure 4. 7:Typical diagram of Electrical Power Network[19].

When more PV electricity is generated than is consumed, the excess can be metered and fed into the grid. When the PV system is not supplying enough power, the excess amount needed can be acquired from the utility grid. A general diagram of the PV system displaying the main components[57]. The Solar PV urban planning project (Gigawatt Global Programmed of Activities) established a renewable solar energy power plant where none previously existed.

Mini-grids are becoming increasingly popular in developed countries, including Rwanda, as a means of improving energy security, power quality, and dependability, as well as avoiding power outages caused by natural catastrophes.


Source: Scatec Solar

Figure 4. 8:Utility-scale of 8.5MW PV power plant constructed in Agahozo-Shalom Youth Village in Rwanda[57].

Rwanda's position just south of the Equator makes it an ideal location for the development of solar PV plants. However, this potential has not yet been fully realized, as the majority of the country's energy is still generated by hydro and thermal power plant. Even during the rainy season, there is consistent and adequate sunshine, particularly in the Eastern Province, which is known for its high irradiance levels. By analysis a total of among connected solar pv to grid are summarized in table 4.5

Table 4. 6:Total number of solar power plants and total capacity [58]

SN	Plant Name	**Installed Capacity (MW)**
1	JALI	0.25
2	NDERA	0.16
3	Gigawatt / Rwamagana	8.5
TOTAL		**8.91**

The power system strength is evaluated in terms of its stability, with a stronger power system typically linked to A lower risk of problems such as voltage instability and undesirable control interactions. For any AC/DC converter, the Short-Circuit Ratio (SCR) is determined by dividing the short-circuit level (in MVA) at the point of common coupling (PCC) by the rated capacity of the installed DC system (in MW)[59].

4.5 Grid strength Analysis

4.5.1 Short Circuit Ratio

The issue of Short Circuit Ratio (SCR) was first raised before the Grid Code Review Panel in May 2008, with the primary complaint being that the current Grid Code mandates a minimum value of 0.5. With the introduction of new Generation technologies capable of producing single machine sizes of up to 2000MVA, there was concern that such a figure would be hard to achieve. National Grid has an obligation to examine the needs of the Grid Code at any time and be responsive to technological advancements that may affect Users[60].

The short circuit level of a bus bar indicates the amount of short-circuit current that flows to the ground when a fault occur at that bus. Its value is influenced by the short-circuit contributions from the system's available resources. This measurement is primarily used to assess the equipment's ability to endure faults and plays a crucial role in calculations like the short-circuit ratio (SCR for consumers)[61].

The mathematical model of system strength assessment defines the SCR as the ratio of the three-phase short-circuit capacity (Ssc) at the PCC to the active power rating (Pd) of the DC system.

$$\textbf{Shortcircuit Ratio (SCR)}= \frac{Scs}{Pd} \tag{4.1}$$

The equation 4.1 This formula is commonly used as a key indicator to assess the potential extent of interactions between the converters and the rest of the power system [62]. The short-circuit capacity of the point of common coupling (PCC) can be expressed as

$$\textbf{SCR}= \frac{{U_{ac}}^2}{Z_{ac}} \tag{4.2}$$

With: U_{ac} the nominal bus voltage, Zac the AC system impedance, which basically represents the Thevenin equivalence impedance as seen from the PCC, are used to calculate the Short-Circuit Ratio (SCR). By taking the the AC system nominal voltage U_{ac} as the base voltage U_b and P_d as the base S_b The Sort-Circuit Ratio can be expressed as:

$$\text{SCR}=\left(\frac{U_{ac}{}^{2}}{U_{b}{}^{2}}\right)\left(\frac{Z_b}{Z_{ac}}\right)/\frac{P_d}{S_b}=\frac{1}{Z_{ac}} \tag{4.3}$$

With $\boldsymbol{Z_{b}}= \frac{U_b{}^2}{S_b{}^2}$ and $\boldsymbol{Z_{ac}}$ the converter ratings determine the per-unit value of the Thevenin equivalent impedance. The equations above indicate that a low SCR implies a system with high impedance, and conversely, a high SCR suggests a system with lower impedance. For example, consider a point in an AC system with a short-circuit capacity of Ssc (in MVA) to which a DC connection of rated power Pd (in MW) will be attached. The equivalent impedance in per unit can thus be determined in the specific scenario where the rated DC power is chosen the base power, can thus be calculated as

: $$\boldsymbol{Zac} = \frac{\boldsymbol{Pd}}{\boldsymbol{S_{sc}}} \tag{4.4}$$

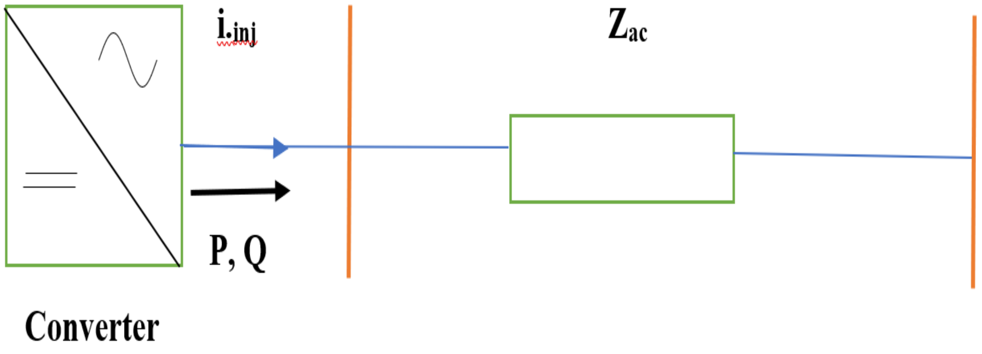


Figure 4. 9: Equivalent circuit of the AC system as seen from the PCC.

Thus, the equivalent system of fig.4.5 is achieved. This shows that the system's impedance can be determined by knowing the short-circuit capacity [61].

4.5.2 Composite Short Circuit Ratio

This This metric assesses grid strength at a connection point, particularly for integrating inverter-based resources (IBRs) like wind and solar power. It extends the traditional Short Circuit Ratio (SCR) by incorporating system dynamics and control interactions for a more comprehensive evaluation. Accurate prediction and simulation of fault currents are essential for safe and reliable power system operation. Proper modeling of system components supports equipment rating selection and protection settings under varying conditions, especially for nonsynchronously powered sources.The proposed type of connection is when the nonsynchronous machine is decoupled from the grid through power electronic devices (inverters in this project) as depicted on fig4.9.

Initially proposed by GE, CSCR calculates the grid strength considering all electrically close converters. Several new stability indices based on SCR for networks with a high penetration of IBRs have been proposed. Simpler indices look at the contribution of fault current and use this to infer information about the voltage stability, interactions and grid stiffness.

Power system tools simulate the interactions between the electrical grid, customers, and generators as utilized in [54]. Figure 4.11 depicts the Rwandan power system with its control areas.

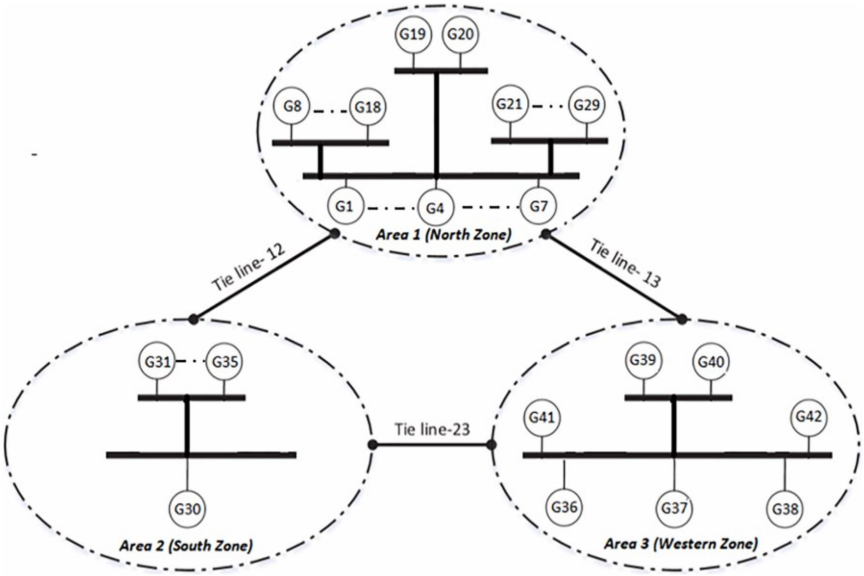


Figure 4. 10:Rwanda power system control area.

$$CSCR = \frac{CSC\ MVA}{MWVER} \tag{4.5}$$

CSC: Fault level contribution excluding converters

MW_{VER}: Is the sum of nominal power ratings of the connected converters

Traditional SCR only considers the short-circuit power at the point of interconnection relative to the inverter capacity. CSCR incorporates system interactions, including grid impedance variations and control dynamics, making it more accurate for assessing system strength.

CSCR are used for:

Grid Stability: Helps determine the ability of the grid to support inverter-based generation without stability issues.

Renewable Integration: A low CSCR indicates that IBRs may face challenges like weak grid conditions, voltage instability, and poor fault ride-through capability.

Planning and Design: Utilities and system operators use CSCR to assess whether grid reinforcements or additional controls (e.g., STATCOMs) are needed to support renewables.

Typical CSCR Values

CSCR > 3: Strong grid, minimal stability concerns.

CSCR between 1.5 – 3: Moderately weak grid; may require additional stability measures.

CSCR < 1.5: Weak grid, high risk of instability, requiring advanced control strategies or reinforcements.

CSCR=1: The grid is extremely weak.

CHAPTER FIVE: DESIGN AND SIMULATIONS

5.1 Introduction

Energy is becoming an essential for increasing income and quality of life. Electricity availability is in high demand in emerging countries in order to promote economic growth and industrial development. In these countries, sustainable economic growth is primarily dependent on uninterrupted energy supply, as electricity serves as a driving engine for economic expansion. The simulation tools to model the impact of SHS on the grid under various scenarios, helping to predict and mitigate potential issues before large-scale integration is required. Designing a 5 kWp Solar Home System (SHS) integrated with the grid involves several considerations. The system needs to ensure seamless operation both for providing energy to the household and feeding surplus energy back to the grid. The architecture would include solar panels, an inverter, a charge controller, a battery bank, Load and a grid-tie mechanism for energy export.

5.2 Design model in homer software

As said above the model in software is composed by solar PV, Generator, Electrical load converter and battery storage. Battery bank and converter technology are also employed for grid-connected sites. Battery storages provide short-term backup power, while converters convert ac to dc power and vice versa. The grid provides electric power to the site load as well as power to storage batteries via a converter for charge.

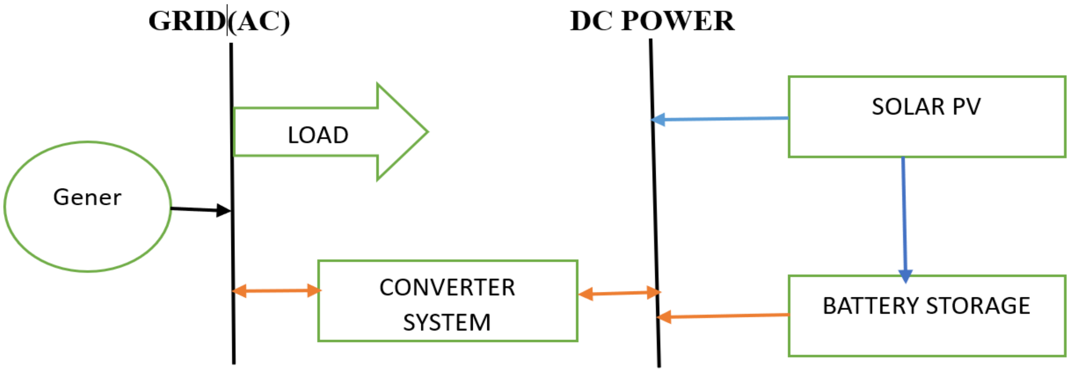


Figure 5. 1: Proposed Design model in Software homer pro

5.3 The Sizing of components

The proposed System design reflect to how Rwanda would involve the integration of high-efficiency solar panels, a grid-tied inverter with MPPT technology, and the possibility of battery storage. The system should be built to ensure that excess energy can be exported to the grid and that the system runs safely and effectively while being compatible with national grid regulations. Proper energy monitoring and safety devices should be incorporated to guarantee smooth and effective operation. This design is based on following assumption.

Table 5. 1:Proposed parameters for design

ITERMS	**Descriptions**
Location	Rwanda (Average solar insolation: 5.5 kWh/m²/day)
System Size	5 kWp (kilowatt peak) solar power capacity
Solar Panel Rating	350 W per panel
Inverter Efficiency	98% (typical for high-quality grid-tied inverters)
Daily Energy Consumption	15 kWh/day
Solar Insolation	5.5 hours/day
Battery Depth of Discharge (DoD)	80% (typical for Li-ion batteries)
Battery Voltage	48V (typical for residential systems)

The grid compensation or net metering, let us Assume that the excess power fed into the grid will be compensated as Rwanda has net metering policy or will be implemented as recommendation at the end of this work.

The Solar cells capture energy using the photovoltaic effect. Solar cells constitute a solar panel, and enough solar panels are required to generate power then let us start by system sizing according to the standard[63],[64].

5.3.1 System sizing

i. Number of Solar Panels

Each panel now generates =350W

Total system capacity required = 5 kWp (or 5000WP).

Number of panels required is given by

Number of Panels=$\frac{Total\ system\ watt\ peak}{Watt\ peak\ of\ each\ panel}=\frac{5000W}{350W}$ =14.3 panels

So, we have use 15 panels rated at 350W each, providing a total capacity of 5.25 kWp.

ii. Solar Array Configuration

Here, we configure the 15 panels in series and parallel strings based on the inverter's input specification this will be arranged as the panels in 2 strings of 7 panels each (7 panels in series per string This configuration can vary, and the exact number of strings and series connections depends on the inverter's voltage and current limits.

iii. Solar Energy Production

let's calculate how much energy the system will generate in a day.

The Solar Insolation (Average Sunlight Hours) consider that in Rwanda, average daily sun hours = 5.5 hours/day

Energy Generated without considering losses is given by

Energy Output (kWh)= System Capacity (kWp)×Average Sunlight Hours

=5.25kWp×5.5hrs/day=28.875kWh/day, from here system will generate approximately 28.9 kWh/day under optimal conditions.

5.3.2 Energy Demand/Load demand, Battery Selection and Surplus

i. Household Energy Demand

The household uses 15 kWh/day, so the energy generated by the system will meet the demand, and there will be surplus energy.
Surplus Energy=Energy Generated (28.9 kWh) −Energy Demand (15 kWh) =13.9kWh/day

This excess energy can be used for battery storage or transferred to the grid after the battery is fully charged.

Assume the customer need to store two days' worth of energy as backup (to cover periods without sunlight or high consumption). Of course, we need to calculate how much energy that can be stored store. The Storage required=2×Daily Consumption=2×15kWh=30kWh. To determine the battery capacity, the Depth of Discharge (DoD) will be taken into consideration. For Li-ion batteries, a typical DoD is 80%, meaning that only 80% of the battery's total capacity will be used.

The Required Battery Capacity=$\frac{Storage\ Needed}{\text{DoD}}=\frac{30Kwh}{0.8}=37.5kWh$, the battery bank should be sized at 37.5 kWh to provide backup power for 2 days.

ii. Battery Voltage and Arrangement

As i have decided a 48V battery bank (a common setup for residential systems), we need to calculate the number of batteries required.

Battery Capacity (in Ah), Since the required energy is 37.5 kWh, we can calculate the capacity of the battery bank in amp-hours (Ah).

Battery Capacity (Ah)= $\frac{\boldsymbol{Required\ Energy\ (kWh)}}{Battery\ Voltage\ (V))}=\frac{37.5kWh}{48V}=780.2Ah$

Then the total battery bank capacity needed is 780 Ah at 48V; by assuming we have batteries with a 3.2 kWh capacity and a 12V rating. The number of batteries needed to meet the required energy storage is given by Number of Batteries=$\frac{37.5kWh}{3.2kWh/battery}=11.72\ batteries$ approxi 12 batteries

The system requires approximately 12 batteries with a 12V nominal voltage each. These would be connected in series-parallel to form a 48V battery bank.

iii. System Performance with Battery Storage

The Energy Flow and Usage within Daytime (Solar Generation): The solar system will provide 28.9 kWh/day of energy and 15 kWh will be used by the household means that the remaining 13.9 kWh will be used to charge the batteries and supplied to the grid.

Battery Charge: Each day, the batteries will be charged with 13.9 kWh, which will be stored for later use. There are two scenarios for Nighttime or Low Solar Generation as follow:

If solar generation is insufficient let us say at night or on cloudy days), the battery bank will supply the household's demand (up to 15 kWh/day). If the battery charge is depleted, the grid will provide power to meet the energy demand.

Inverter Selection Criteria: The inverter should handle at least 5 kW of AC power output, by Ensuring that the inverter’s maximum DC input voltage range matches the array configuration (300V DC for the strings of panels) and it should be with MPPT (Maximum Power Point Tracking) technology to optimize the power conversion efficiency.

iv. Surplus Energy Export to the Grid

Once the batteries are fully charged, the remaining surplus energy will be sent to the grid. In Surplus Energy Export: 13.9 kWh/day can be exported to the grid.

v. Grid Integration and Monitoring

The Installation of Bi-Directional Meter that will track and allow energy to follow for both consumer and the main grid, ensuring proper compensation under a net metering policy, battery management system (BMS) that will ensure that the batteries are not overcharged or discharged too deeply.

It will manage the charging and discharging cycles efficiently and Energy Management System (EMS) that will include real-time monitoring of solar generation, battery state of charge, energy consumption, and grid interaction.

vi. Analysis of the Designed System

For the range of 0 up to 50kwh par moth, the cost for residential is 89 Rwf up to 212 Rwf. Let us take Rwanda electricity tariff as 200 RWF/kWh.

Energy Export to Grid**:** If the system is able to export 13.9 kWh/day after charging the batteries, the daily compensation would be given :13.9 kWh/day×200 RWF/kWh=2780 RWF/day. The annual energy export is calculated as:

The Annual Compensation=2780RWF/day×365days=1,014,700RWF/year.

The battery system (with 12 batteries) adds significant cost, but the reliability and energy independence provided by the battery backup may offset those costs over time, especially in cases of frequent power outages or rising grid prices.

5.4 Simulations Results

In this thesis three different software have been used for result simulation;

Homer Pro**:** The energy modeling software used for optimizing hybrid power systems, including solar, wind, batteries, and diesel generators. It is widely used for Microgrid Design & Optimization and financial Analysis and Renewable Energy Feasibility Studies.

DigSilent Power Factory: is a powerful power system analysis software widely used for grid modeling, simulation, and optimization. It is commonly used by utilities, consultants, and researchers for studies related to power flow, stability, protection, and renewable energy integration.

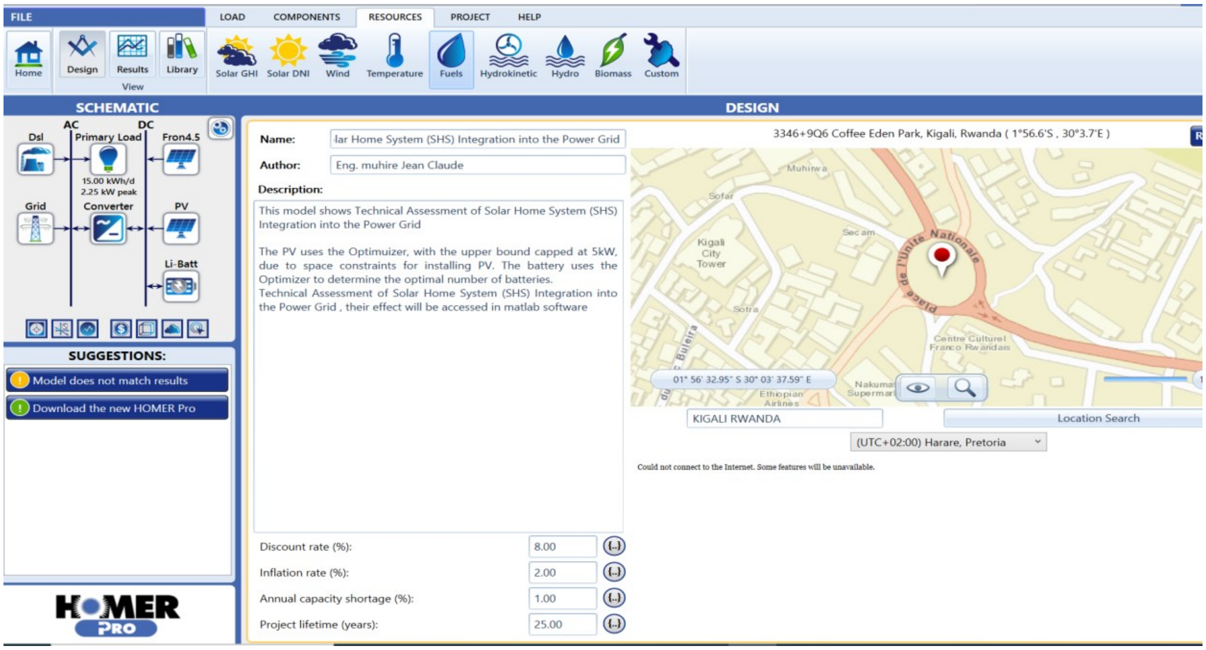
Plex Software: is a high-level programming language and environment developed by MathWorks, mainly used for numerical computing, data analysis, simulation, and visualization.

5.4.1 Simulation using Homer Software

The collected data were used as inputs in HOMER Pro to simulate Daily and monthly inverter input/output profiles, System performance under various load conditions, Grid compatibility of existing SHS architectures and Opportunities for technical optimization and integration.

The simulation requires additional parameters like load variation, cost and busbars configuration.

The results will provide the optimizations. The overview of the solar home system as renewable energy system was simulated using HOMER Pro. The primary objective was to evaluate the feasibility of a solar- system for providing reliable and sustainable energy to a remote community and on grid. The model configuration is shown as



Model does not match results

Download the new HOMER Pro

Name: lar Home System (SHS) Integration into the Power Grid

Author: Eng. muhire Jean Claude

Description:

This model shows Technical Assessment of Solar Home System (SHS) Integration into the Power Grid

The PV uses the Optimuizer, with the upper bound capped at 5kW, due to space constraints for installing PV. The battery uses the Optimizer to determine the optimal number of batteries.
Technical Assessment of Solar Home System (SHS) Integration into the Power Grid , their effect will be accessed in matlab software

Discount rate (%): 8.00

Inflation rate (%): 2.00

Annual capacity shortage (%): 1.00

Project lifetime (years): 25.00

3346+9Q6 Coffee Eden Park, Kigali, Rwanda (1°56.6'S , 30°3.7'E)

01° 56' 32.95" S 30° 03' 37.59" E

KIGALI RWANDA

(UTC+02:00) Harare, Pretoria

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Figure 5. 2: Modal configuration of solar home system connected on grid

The above model was chosen n with objective of cost reduction, efficiency improvement, sustainability, economic viability of the system and its environmental impact. The setup parameters and assumptions have Cleary provided in the design parts.

5.4.2 Simulation by Using Plex Software

It is possible to represent photovoltaic (PV) systems in Power Factory for the purpose of power system analysis. It is important to decide from the very beginning on the type of analyses being carried out in the study because Power Factory offers multiple possibilities for PV modelling.The integration of multiple photovoltaic (PV) systems into the electrical grid presents technical challenges such as voltage stability, power quality, and grid reliability.

Dig SILENT Power Factory is a powerful tool for simulating and analyzing power systems, including grid-connected PV systems.

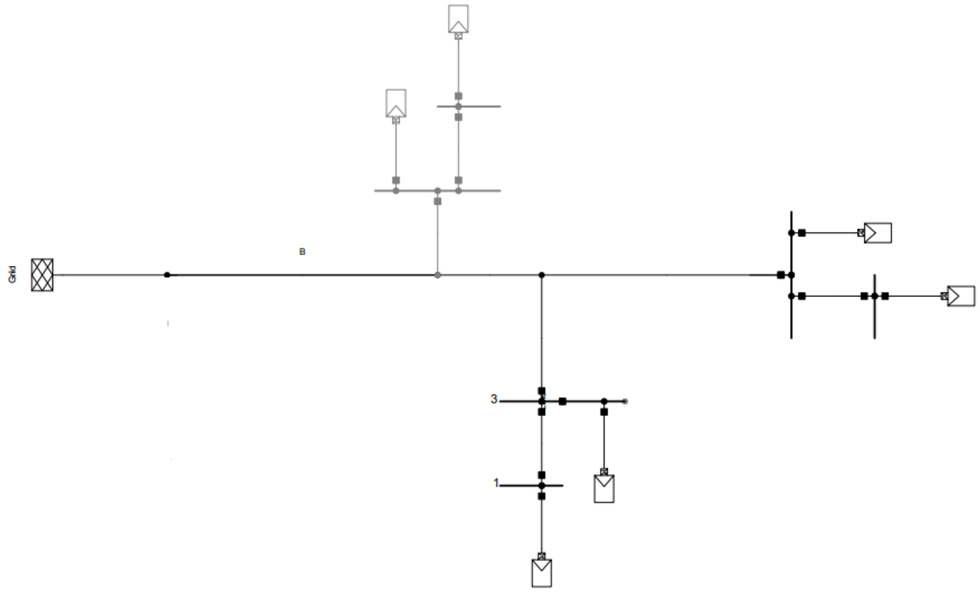


Figure 5. 3:PV Connection to grid by using Dig silent software

Each PV system includes a DC source (solar panels), an inverter, and a connection to the AC grid. The Voltage levels, short circuit power, and transformer ratings are defined as we Performed to study voltage variations and power distribution. For dynamic Analysis Conducted to assess grid stability with PV penetration. Harmonic Analysis Evaluates power quality impact due to PV inverters.

To simulate multiple PV systems, replicate the PV model and connect them to the grid at different locations, adjusting the power rating and characteristics based on the specific system design as calculated for each module. The results are analyzed by using both MATLAB and Dig silent software,

After the simulation, utilize Power Factory’s post-processing tools to visualize and analyze the results, including power curves, voltage fluctuations, power loss and Real &active power. Also distributed solar home system have simulated by using MATLAB

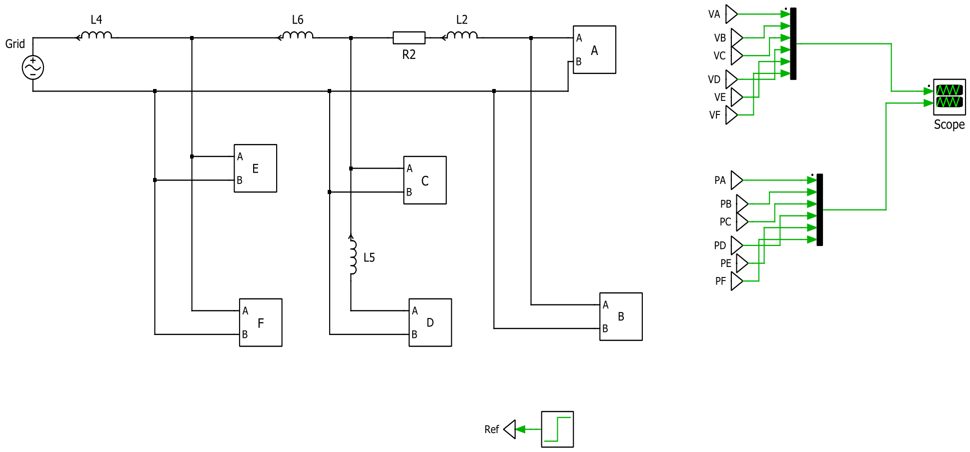


Figure 5. 4:Simulated system of distributed SHS

The figure 6.4 shows a schematic diagram of an electrical power system. The image is a complex electrical schematic diagram. It displays various components such as transformers (L2, L4, L5, L6), resistors (R2), and several blocks labeled with letters (A, B, C, D, E, F), indicating different parts of the system.

The Wires connect these components in a network suggest a flow of electricity or signal transmission.

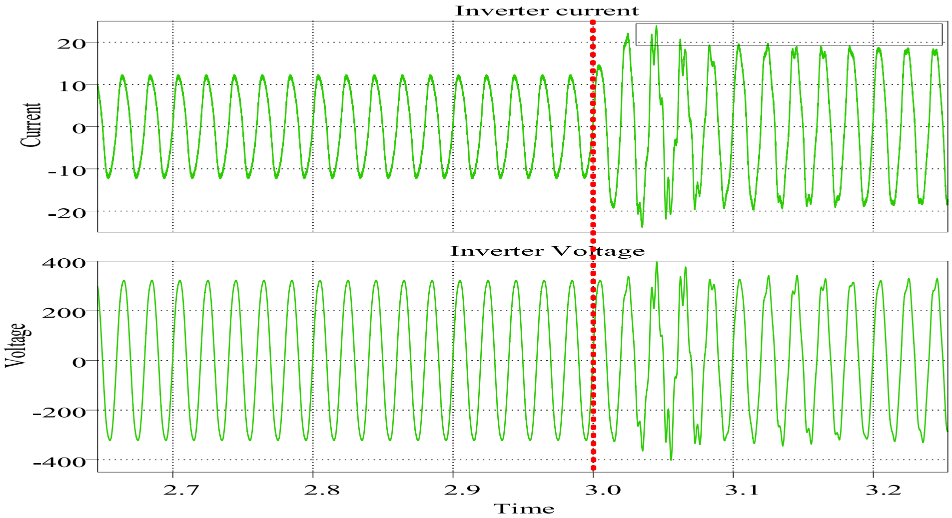


Figure 5. 5:Input voltage and current for the inverter

This figure presents the inverter's current and voltage waveforms over time. The upper subplot shows the inverter current with an amplitude of approximately ±20 A, while the lower subplot illustrates the inverter voltage, which oscillates around ±400 V. Initially, both signals exhibit a stable sinusoidal pattern, indicating normal operation. However, after the red-dashed vertical line (around t = 3.0 s), disturbances appear in both current and voltage waveforms. These distortions suggest a transient event, possibly caused by a grid disturbance, load change, or inverter control instability.

The increased oscillations and irregular waveform shape beyond t = 3.0 s indicate the system's response to the disturbance, highlighting the need for further analysis to improve stability and minimize harmonics in the inverter output.

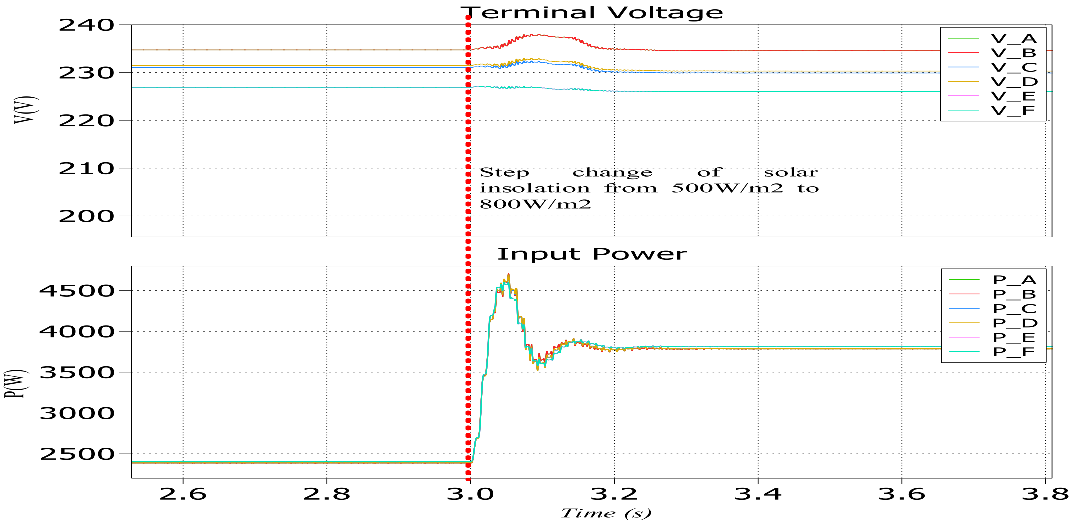


Figure 5. 6:Terminal Voltage and Input Power

The figure 5.6 displays two graphs showing the terminal voltage and input power of a system, likely a photovoltaic system, that undergoes a step change in solar insolation. The image contains two-line graphs, vertically stacked. The top graph is titled as Terminal Voltage and displays six lines representing voltages (V_A through V_F) over time. The y-axis represents voltage (V) ranging from approximately 200V to 240V. The x-axis represents time (s) from approximately 2.6s to 3.8s. Each line shows voltage fluctuations largely staying within a narrow range. Around 3 seconds, there's a noticeable and brief spike in voltage.

The bottom graph is titled Input Power, displaying six lines that represent power (P_A through P_F) over time. The y-axis represents power (P(W)), ranging from approximately 2500W to 4500W. The x-axis is the same as the top graph, showing time from approximately 2.6s to 3.8s. Before the 3-second mark, power levels are relatively low and stable. Around the 3-second mark, there's a considerable and brief increase in power, followed by a more gradual return to a lower, stable level.

A dashed red vertical line runs through both graphs at approximately 3.0 seconds, indicating the time of a step change in solar insolation. A text box next to this line in the upper graph explains that this represents a step change in solar insolation from 500W/m2 to 800W/m2. The overall atmosphere of the image is technical and data-driven, with a neutral mood. The graphs clearly show the response of the system to the increased solar input.

5.5 Results from Dig SILENT Power Factory

The voltage profile at each bus bar is recorded at each busbar, during peak solar production hours, each PV system contributes to local voltage support. Busbars connected to high-generation PV systems may show voltage increases due to the generation of excess active power (real power) and reactive power management.

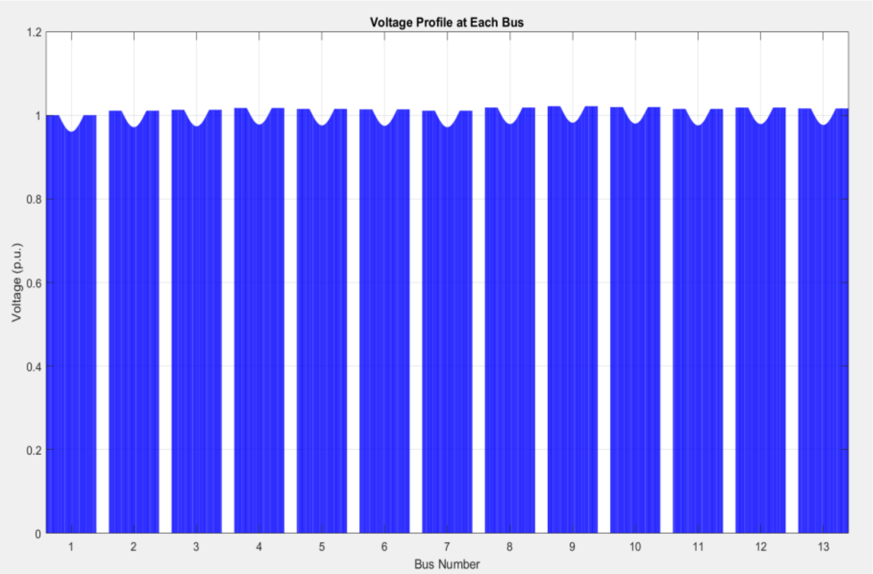


Figure 5. 7:Voltage Profile at Each Bus

The voltage profile of each busbar is represented as a bar plot in per unit (p.u.). The main busbar (15 kV) is not included in the voltage profile since it is assumed to have no load. The voltages at the buses deviate small from the nominal value due to power losses in the system. Some buses experience voltage drops due to increased loading and impedance of the network. The presence of PV systems helps to regulate voltage, but fluctuations occur based on generation and load variations.

The voltage profile highlights the impact of PV integration on system stability. Proper reactive power compensation may be required to maintain voltage levels within acceptable limits.

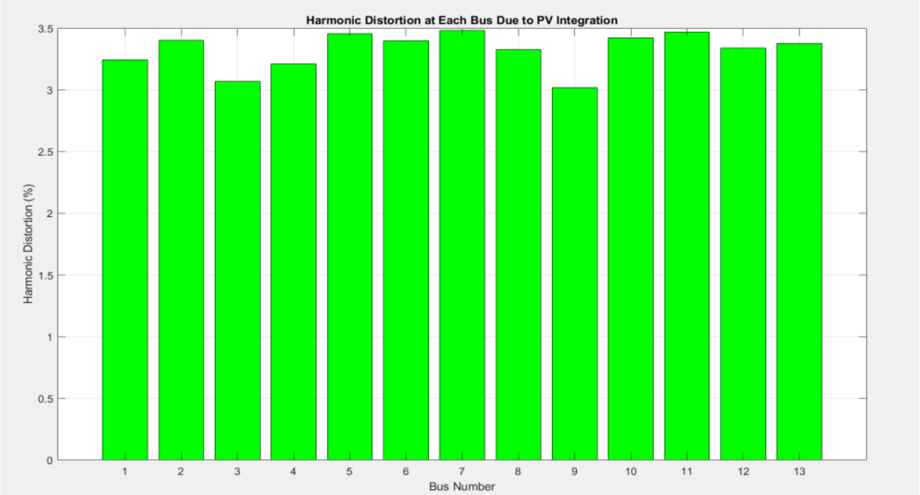
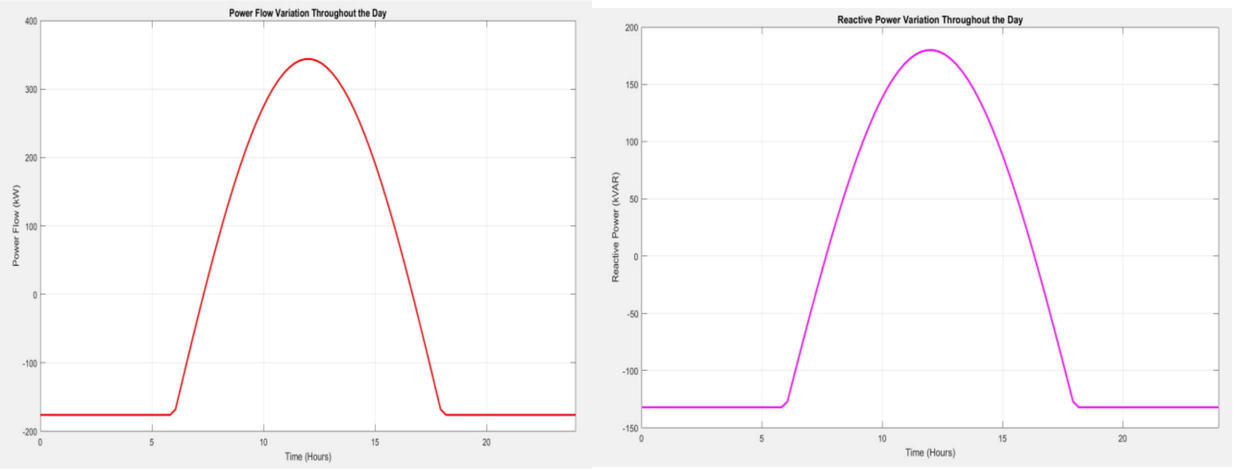


Figure 5. 8:Harmonic Distortion

The figure 5.8 displays the Total Harmonic Distortion (THD) for each bus, highlighting how PV integration impacts power quality. Each bus has a different THD level, depending on load variations and PV penetration. The buses with high PV penetration tend to exhibit higher harmonic distortion due to inverter-based generation. The THD levels remain within moderate limits, but some buses may require mitigation techniques. Harmonics can lead to power quality issues, overheating of equipment, and resonance problems. Possible mitigation strategies include installing filters, using advanced inverter technologies, and grid reinforcement measures.



(a) Active power flow (b) Reactive power

Figure 5. 9:Active and Reactive power variation through the day

The Figure 5.9 (a) depicts how active power (kW) varies over 24 hours as PV generation changes with solar irradiance. During early morning (00:00 – 06:00), PV generation is absent, and power demand is solely supplied by the grid.

From 06:00 to 12:00, PV generation gradually increases, reaching its peak at noon (around 12:00 PM). In the evening (after 18:00), PV power declines, leading to more grid dependency. To access the contribution of pv to grid , 5 PV systems disconnected is disconnected and the reduction in PV capacity (5 PV systems disconnected) results in lower power generation, increasing grid dependency. The results indicate that PV penetration significantly reduces power demand from the grid during peak sunlight hours, reducing strain on the conventional power system. However, at night and during low solar periods, backup sources are needed.The Figure 5.9(b) illustrates the variation of reactive power (kVAR) with time. The trend follows a similar pattern to active power generation because PV inverters contribute some level of reactive power support.

The highest reactive power generation occurs at noon, correlating with peak PV output. The system exhibits higher reactive power demand in the evening and early morning, indicating grid dependency. The Voltage stability can be impacted by the reactive power behavior.

The grid may need additional reactive power compensation (like capacitor banks or STATCOMs) to maintain voltage levels, particularly at night.

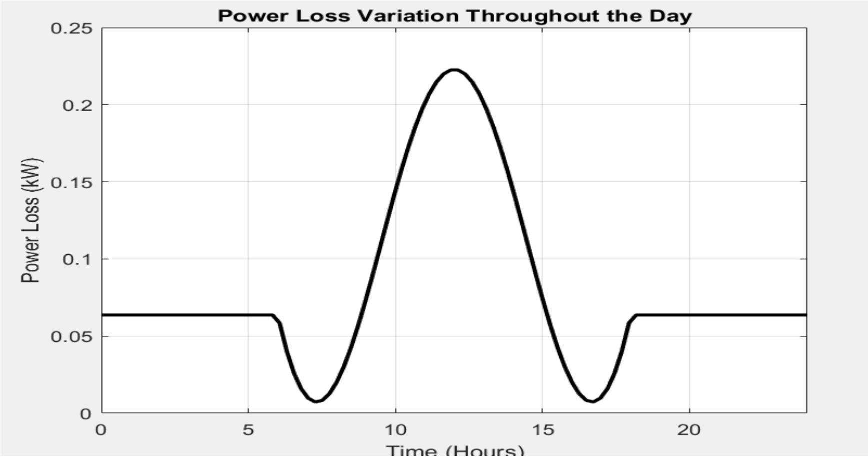


Figure 5. 10:Power loss variations

This shows the power losses in the system over time as PV generation fluctuates. Losses are highest when PV generation is lowest (at night and early morning). During midday, when PV generation is high, power losses decrease due to reduced power flow from the grid. The disconnection of 5 PV systems results in increased losses compared to a fully operational PV system and higher grid dependency leads to increased power losses. Optimal PV placement and network reinforcement strategies (such as voltage regulation techniques) can help minimize losses and improve efficiency.

The results illustrate the dynamic nature of voltage stability, power flow, and losses in a grid-integrated PV system. PV penetration helps reduce grid dependency but introduces challenges such as voltage fluctuations, harmonic distortion, and reactive power imbalance. The disconnection of 5 PV systems increases power losses, voltage deviations, and grid demand, indicating the significance of maintaining optimal PV operation. To enhance system performance, power quality solutions (harmonic filters, voltage regulators) and smart grid strategies (demand-side management, battery storage) should be explored.

5.5.1 Harmonic distortion

Harmonic distortion is a common power quality issue in grid-connected photovoltaic (PV) systems. The presence of nonlinear power electronic converters in PV inverters introduces harmonics into the grid, which can lead to increased power losses, overheating of equipment, and voltage waveform distortions. The harmonic mitigation technique was applied to reduce the total harmonic distortion (THD) levels at different busbars. Fig 5.11presents a comparative analysis of the harmonic distortion before and after applying filtering.

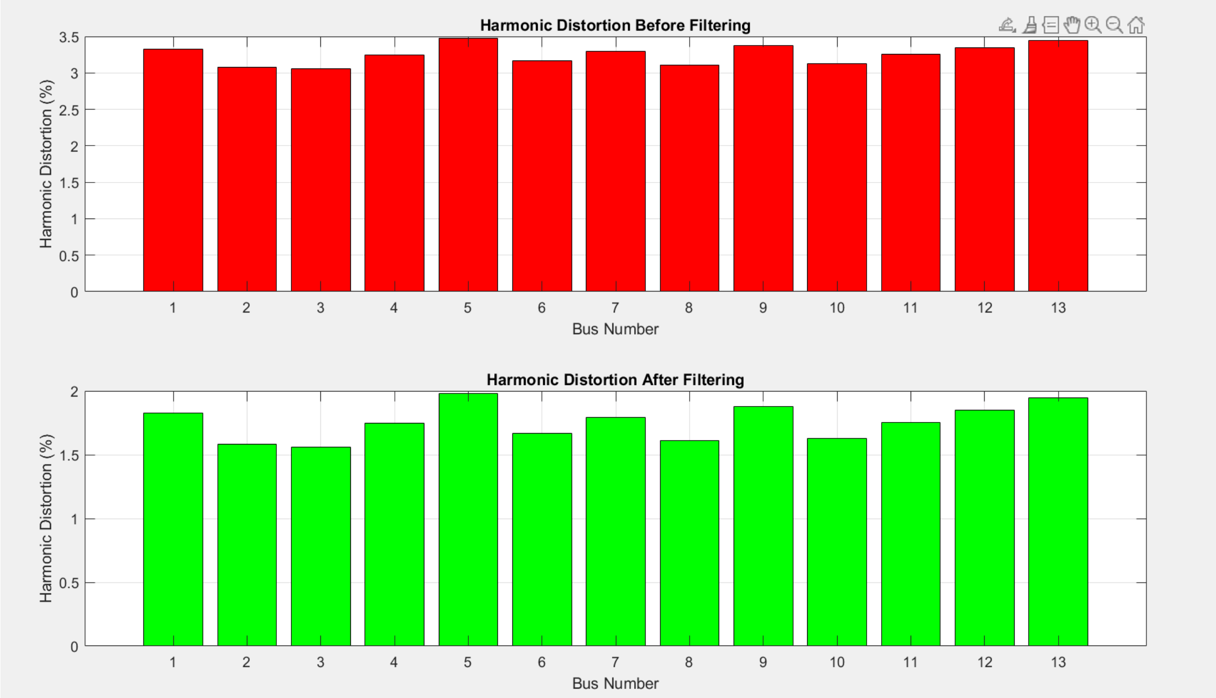


Figure 5. 11:Harmonic distortion before and after filtering

Before Filtering: The system experienced relatively high THD levels, ranging from approximately 3% to 3.5% at different busbars. This level of distortion can negatively impact sensitive loads and grid stability. After Filtering: The harmonic levels were reduced significantly by incorporating a passive filtering mechanism, which lowered THD by approximately 1.5% at each busbar.

The reduction in harmonics enhances power quality, ensures compliance with grid codes, and improves the efficiency of power transmission. The results demonstrate the effectiveness of implementing filtering techniques in mitigating harmonic distortion caused by PV integration. By reducing THD, the overall grid power quality is enhanced, reducing the likelihood of equipment failures and power losses.

5.5.2 Frequency stability

The integration of renewable energy sources, particularly PV systems, introduces frequency stability challenges due to their intermittent nature. Unlike traditional synchronous generators, PV inverters do not inherently contribute to system inertia, making the grid more susceptible to frequency deviations caused by rapid changes in solar generation. Fig 5.12 illustrates the frequency variation over time, highlighting the impact of PV integration on grid frequency stability.

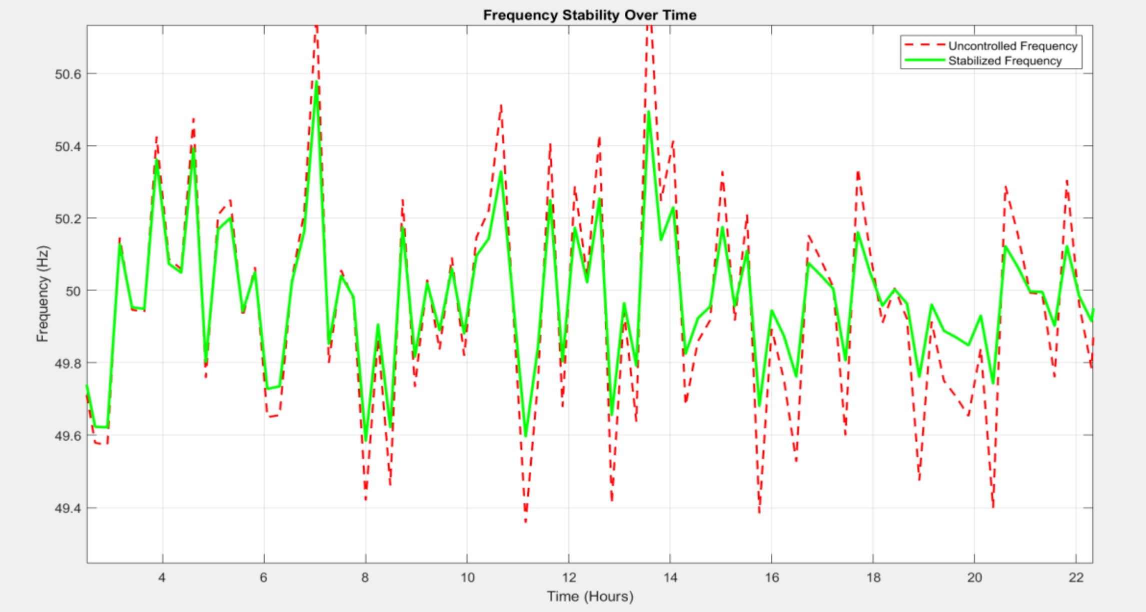


Figure 5. 12:Frequency controlled and uncontrolled

The uncontrolled Frequency (Red Dashed Line) Without corrective control, frequency deviations were observed throughout the day, fluctuating around ±0.3 Hz from the nominal 50 Hz. These variations occur due to changes in solar irradiance, affecting the power output of PV systems and leading to frequency instability.

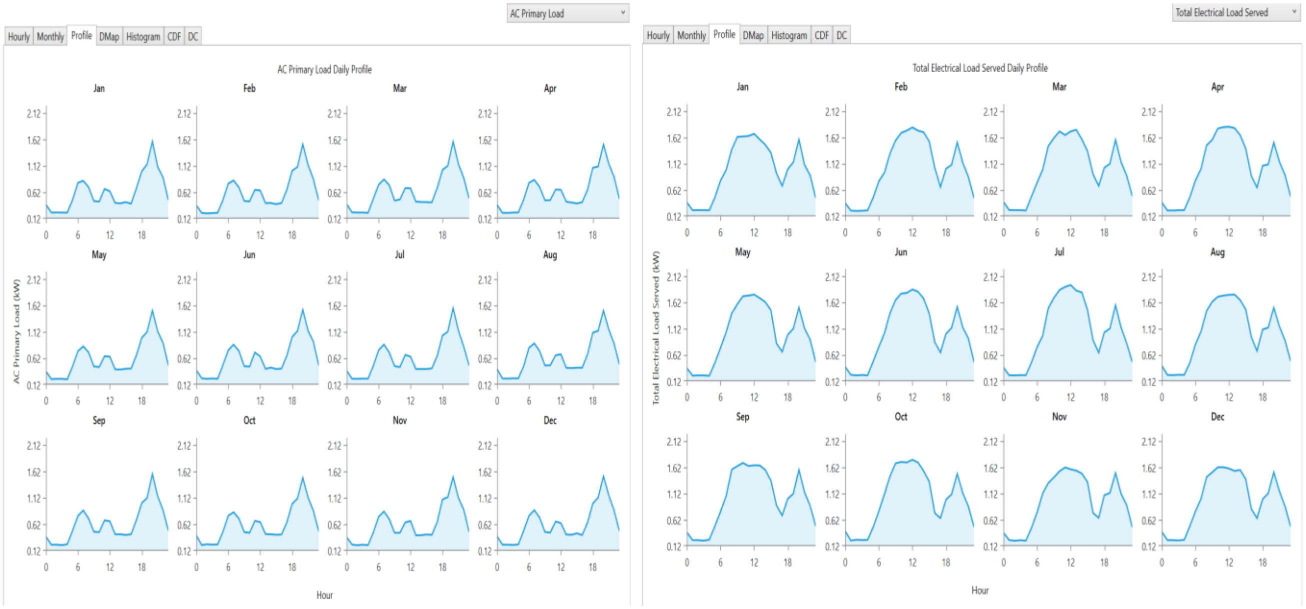
The Stabilized Frequency (Green Solid Line): After applying a corrective frequency control mechanism, the frequency deviations were significantly damped, bringing the system closer to its nominal value of 50 Hz. The control strategy introduced an exponential damping factor, which reduced fluctuations and enhanced grid frequency stability. The stable frequency is essential for ensuring the reliability of the power system.

The results indicate that implementing frequency regulation techniques, such as droop control and synthetic inertia from PV inverters, can effectively counteract frequency deviations and improve grid resilience.

5.6 Simulations Results from Homer software pro

The SHS system produced an average of 30 kWh per day from the solar panel array, meeting **100%** of the daily household energy demand. The excess energy generated during the day (approximately **13.8 kWh**) was stored in the battery system for later use, while excess power was exported to the grid.

The battery storage system effectively reduced grid dependency, with the battery being fully charged during sunny periods and used to supply power during cloudy days or at night. Energy Produced from Solar Panels: 5 kW PV system produced 10,950 kWh annually also energy Stored in Battery: A total of 722.8 kWh was stored in the battery annually apart for grid interaction: The system exported 5073.5 kWh of excess energy to the grid and of course there is certain amount of kWh from the grid when the solar generation was insufficient.



(a)Ac primary load (b) Total Electrical load served daily profile

Figure 5. 13:AC primary load and Total electrical load served daily profile

The AC Primary Load varies throughout the day, reflecting typical residential consumption patterns. The highest demand occurs in the evening, with an average consumption of **1.62 kWh**, which coincides with peak usage when lighting, televisions, and other appliances are in use.

The integration of the Solar Home System has reduced grid dependency by covering a large portion of the AC load through self-generated solar power.

Display pre-set plot: Load(s)

Date: 4/21/2007 6:00:00 AM
Values: 0.84 kW

This plot has been edited. Add plot to

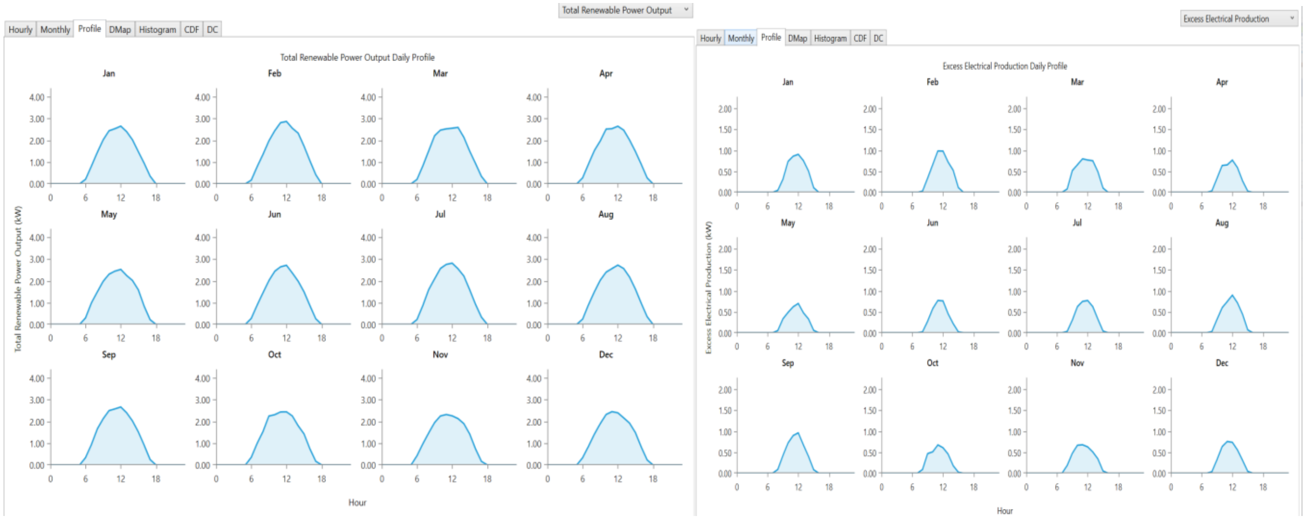
Figure 5. 14:Electrical Load Profile

The total electrical load served, totaling **15 kWh/day**, was effectively managed through a combination of solar generation, battery storage, and grid. On average, **10 kWh** of this demand was met by solar power, with the remainder covered by battery storage or grid imports during periods of low solar generation. This highlights the effectiveness of the Solar Home System in providing a significant portion of the household's energy needs, thereby reducing reliance on the grid.

The ac primary load and total electrical load served provide crucial insights into the system’s ability to meet household energy needs and its reliance on different energy sources (solar, grid, and battery).

This sized system will typically reduce grid dependency, maximize solar energy utilization, and offer a reliable backup through battery storage.

The total daily electrical load includes both AC and DC demands, with a total of **15 kWh/day**. Of this, the system meets **80%** of the load through solar generation, while the remaining **20%** is supplied by the grid, mostly during times of low solar irradiance or when battery storage is depleted. This indicates that the system is nearly self-sufficient, but grid backup is still necessary for energy reliability.

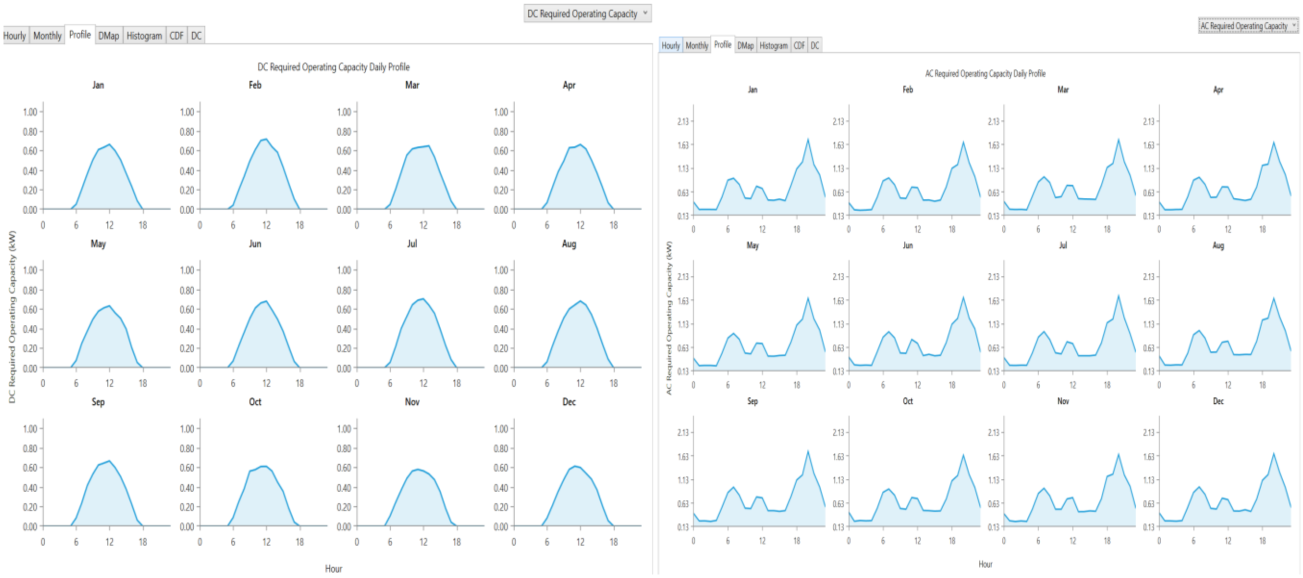


(a)Total renewable energy output Daily (b) Excess electrical production daily

Figure 5. 15:Total renewable energy daily output and excess electrical production

The total Renewable energy output daily represents the total amount of energy generated by the renewable sources (solar panels) on a daily basis. This value is key to understanding how much power the solar system contributes to meeting the total load demands. The total renewable energy output is **30 kWh/day**, which accounts for approximately **100%** of the household's daily energy consumption of **13.9 kWh/day**. This shows that the solar system is generating a substantial portion of the energy needs, thus reducing reliance on grid electricity.

The energy produced is directly used to meet the load, with any excess energy stored in the battery for later use or exported to the grid



(a) DC operational capacity within year (b) AC operational capacity within year

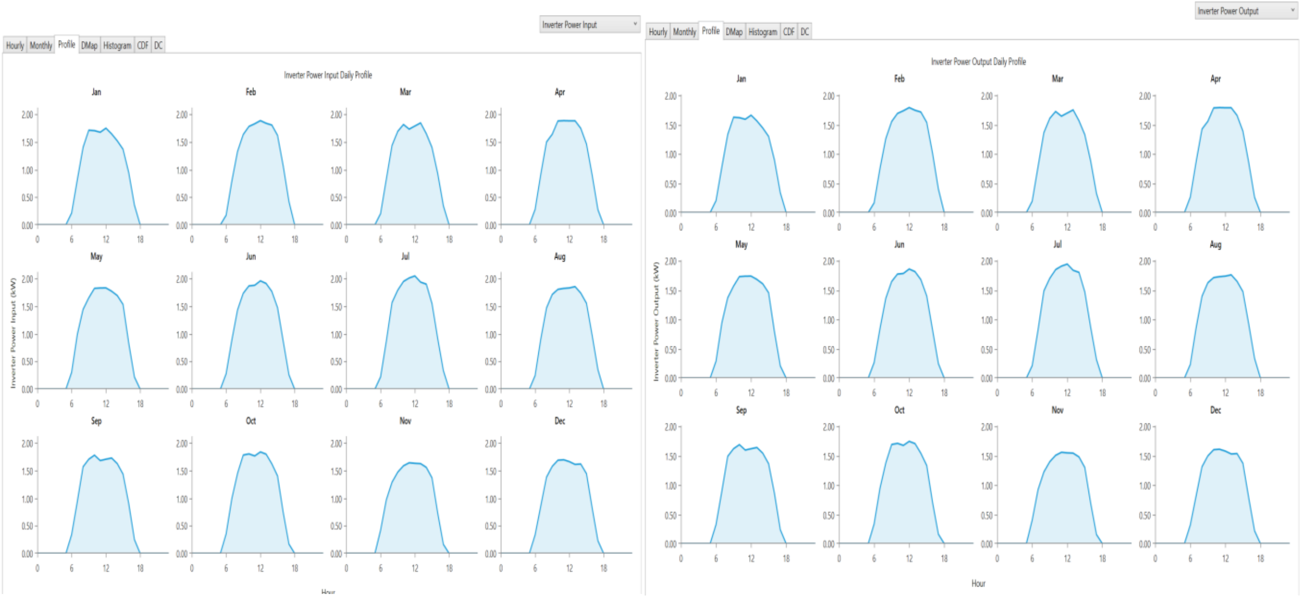
Figure 5. 16:the variations in AC and DC capacity of the system throughout the year

The monthly simulation results obtained from HOMER illustrate the variations in AC and DC capacity of the system throughout the year. These results provide critical insights into system performance, seasonal variations, and potential grid interactions. Both AC and DC capacity fluctuates due to changes in solar radiation and load demand across different months. Peak generation occurs in high solar months, while lower generation is observed in cloudy or winter months. For AC capacity (after inverter conversion is slightly lower than DC due to conversion losses 5-10%) In months with high demand, the system relies on battery storage and grid support to maintain AC output. The seasonal impact on DC generation necessitates a well-sized battery and efficient inverter to ensure energy reliability.

These insights support the feasibility of grid-connected solar systems in optimizing household energy supply while reducing dependency on the grid, the rectifier does not require to work as shown on figure 5.17 bellow.

Figure 5. 17:Rectifier power output

During low solar periods, AC demand is supplemented by grid power or battery discharge. Here efficiency of the inverter plays a crucial role in determining the final usable AC output. The figure 5.18 depicts results from Homer pro.



(a)Inverter input **(b)Inverter output**

Figure 5. 18:Input and output power to the inverter

The inverter's input and output performance across different months has provided as on figure above. The inverter plays a critical role in converting DC power from solar PV and batteries into usable AC power for household consumption or grid export. For input to the inverter varies monthly, depending on solar PV generation, battery discharge, and load demand.

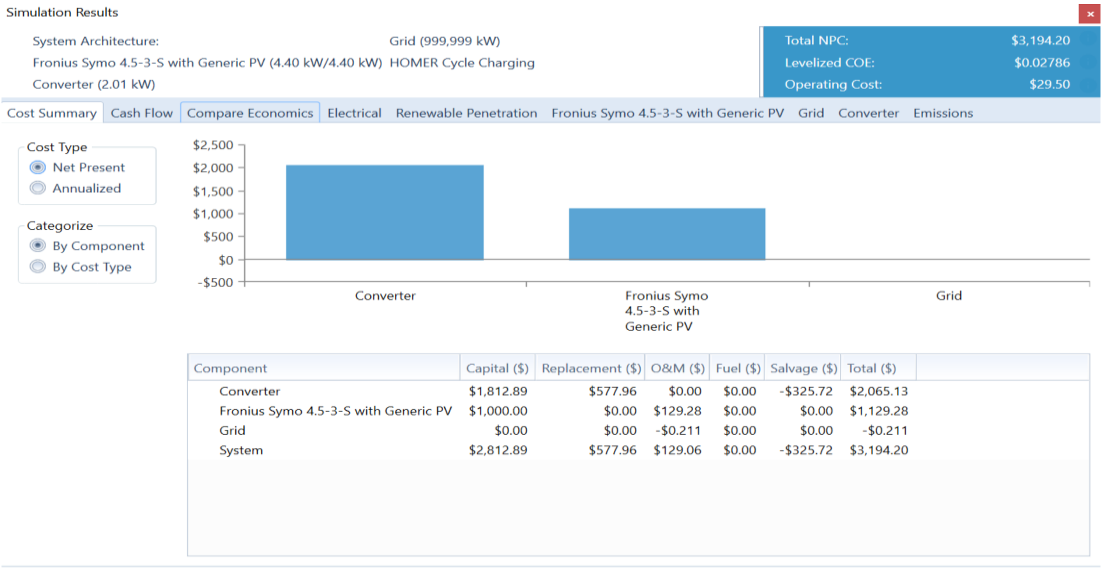
During summer months, with high solar irradiance, the inverter operates at its optimal capacity. The simulation highlights monthly variations in inverter input power, which directly influence the AC output power available for household consumption or grid export. The inverter input follows a daily solar generation pattern, with peak input occurring during midday hours (10:00 AM - 2:00 PM). The highest input is observed in March, April, May, and July, correlating with stronger solar radiation Also Lower input values are seen in November, December, and January, due to reduced solar availability during winter months.

From the figure5.18 (b), the output follows the input pattern, with peak AC power generated during midday hours (10:00 AM - 2:00 PM). The highest AC output is recorded in March, April, May, and July, reflecting strong solar resource availability. The lowest output is observed in November, December, and January, correlating with lower solar generation and shorter daylight hours. As

Comparison of Input vs. Output, the inverter output is slightly lower than its input due to conversion losses (5-10%). The inverter output analysis confirms that a grid-connected solar system can provide consistent AC power throughout the year, with some seasonal fluctuations.

5.7 Economic analysis and Optimization

The economic analysis and optimization of a Solar Home System (SHS) aim to minimize costs while ensuring reliable energy supply. Key considerations include capital, maintenance, battery replacement costs, and potential savings or earnings. Optimization involves selecting the ideal system size and components to reduce the levelized cost of energy (LCOE). Using HOMER software, simulations incorporate solar resources, load profiles, and financial incentives to identify the most cost-effective configuration, maximizing ROI and sustainability.



System Architecture: Grid (999,999 kW)
Fronius Symo 4.5-3-S with Generic PV (4.40 kW/4.40 kW) HOMER Cycle Charging
Converter (2.01 kW)

Total NPC: $3,194.20
Levelized COE: $0.02786
Operating Cost: $29.50

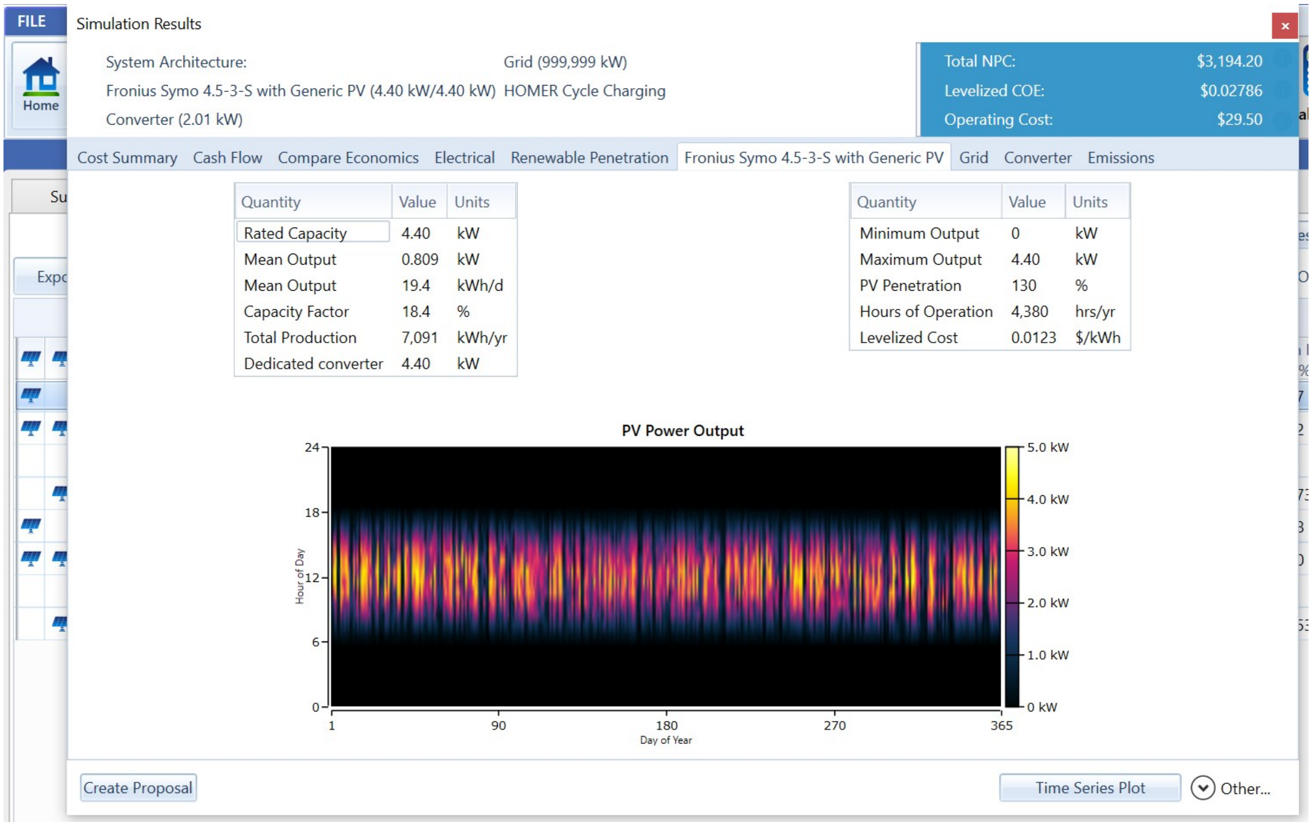
Cost Type: ● Net Present ○ Annualized
Categorize: ● By Component ○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Converter	$1,812.89	$577.96	$0.00	$0.00	-$325.72	$2,065.13
Fronius Symo 4.5-3-S with Generic PV	$1,000.00	$0.00	$129.28	$0.00	$0.00	$1,129.28
Grid	$0.00	$0.00	-$0.211	$0.00	$0.00	-$0.211
System	$2,812.89	$577.96	$129.06	$0.00	-$325.72	$3,194.20

Figure 5. 19:The economic analysis

The figure 5:19 gives an economic study of the solar home system (SHS), emphasizing key financial indicators such as the Net Present Cost (NPC) of $3,194.20, the Levelized Cost of Energy (LCOE) of $0.02786/kWh, and the operational cost of $29.50. The cost breakdown includes capital, replacement, operation and maintenance (O&M), and salvage costs for components like the converter and the Fronius Symo 4.5-3-S with generic PV.

The converter has the largest cost, totaling $2,065.13, followed by the PV system at $1,129.28. The grid has a minimal cost of $0.211. This analysis helps to determine the financial feasibility of the system.



System Architecture: Grid (999,999 kW)
Fronius Symo 4.5-3-S with Generic PV (4.40 kW/4.40 kW) HOMER Cycle Charging
Converter (2.01 kW)

Total NPC: $3,194.20
Levelized COE: $0.02786
Operating Cost: $29.50

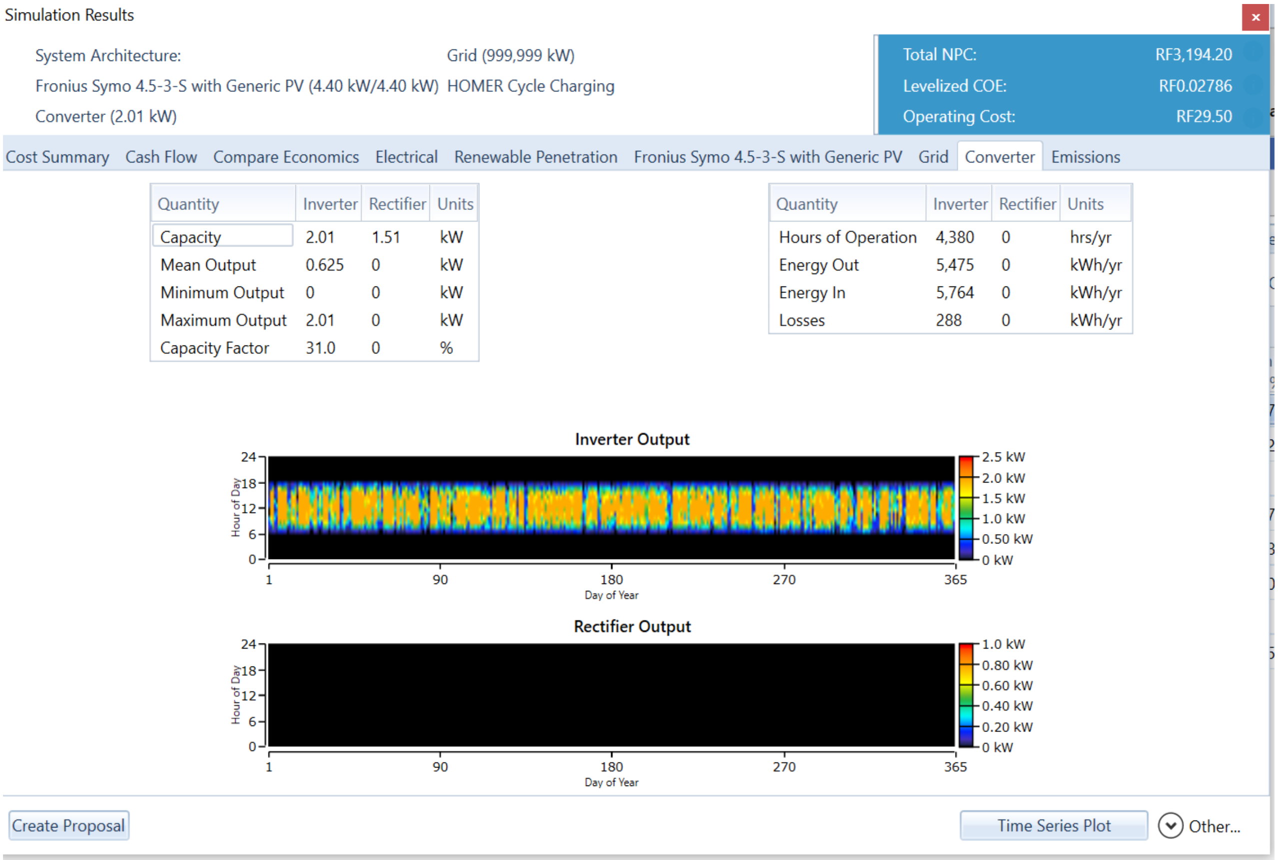
Quantity	Value	Units
Rated Capacity	4.40	kW
Mean Output	0.809	kW
Mean Output	19.4	kWh/d
Capacity Factor	18.4	%
Total Production	7,091	kWh/yr
Dedicated converter	4.40	kW

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	4.40	kW
PV Penetration	130	%
Hours of Operation	4,380	hrs/yr
Levelized Cost	0.0123	$/kWh

Figure 5. 20:The power output and efficiency of the solar photovoltaic

Figure 5:20 shows the power output and efficiency of a solar photovoltaic (PV) system. The Fronius Symo 4.5-3-S has a rated capacity of 4.40 kW and produces an average daily production of 19.4 kWh, totaling 7,091 kWh per year. The capacity factor of 18.4% demonstrates its use efficiency. The PV penetration reaches 130%, implying that solar generation surpasses the primary load demand, potentially enabling energy export to the grid.

The color plot visualizes PV power output variations throughout the year, demonstrating seasonal and daily fluctuations.


Simulation Results

System Architecture: Grid (999,999 kW)
Fronius Symo 4.5-3-S with Generic PV (4.40 kW/4.40 kW) HOMER Cycle Charging
Converter (2.01 kW)

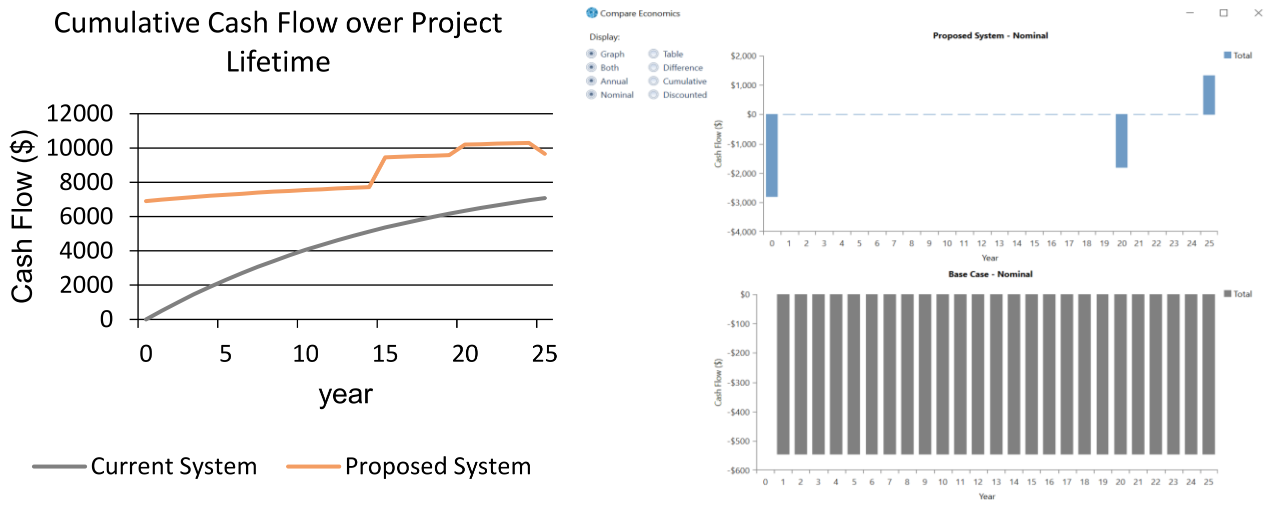
Total NPC: RF3,194.20
Levelized COE: RF0.02786
Operating Cost: RF29.50

Quantity	Inverter	Rectifier	Units
Capacity	2.01	1.51	kW
Mean Output	0.625	0	kW
Minimum Output	0	0	kW
Maximum Output	2.01	0	kW
Capacity Factor	31.0	0	%

Quantity	Inverter	Rectifier	Units
Hours of Operation	4,380	0	hrs/yr
Energy Out	5,475	0	kWh/yr
Energy In	5,764	0	kWh/yr
Losses	288	0	kWh/yr

Figure 5. 21:Performance of the system's power conversion

This evaluates the performance of the system's power conversion components, such as the inverter and rectifier. The inverter has a rated capacity of 2.01 kW and a capacity factor of 31%, resulting in an average output of 0.625 kW. Energy losses of 288 kWh per year are recorded due to conversion inefficiencies. The visualized inverter output plot indicates consistent operation throughout the year, while the rectifier output remains negligible, suggesting limited energy flow in that direction, this performance evaluation is critical for ensuring optimal energy conversion efficiency



(i) (ii)

Figure 5. 22:Economic analysis compares the nominal cash flows

The figure 5.22 depicts economic analysis compares the nominal cash flows of the current system and the base case over a 25-year period. The current system experiences an initial high capital expenditure, followed by periodic maintenance or replacement costs, with financial benefits appearing in later years. In contrast, the base case shows consistent annual costs without significant long-term savings. This indicates that while the renewable energy system requires upfront investment, it offers financial advantages over time compared to conventional alternatives.

Simulation Results

System Architecture: Grid (999,999 kW)
Fronius Symo 4.5-3-S with Generic PV (4.40 kW/4.40 kW) HOMER Cycle Charging
Converter (2.01 kW)

Total NPC: $3,194.20
Levelized COE: $0.02786
Operating Cost: $29.50

Rate Schedule: All

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge $	Demand Charge $
January	293	275	18	2	$0	$0
February	254	272	-18	2	$0	$0
March	294	283	12	2	$0	$0
April	279	290	-11	2	$0	$0
May	282	293	-11	2	$0	$0
June	279	290	-11	2	$0	$0
July	282	322	-40	2	$0	$0
August	292	294	-2	2	$0	$0
September	281	274	7	2	$0	$0

Figure 5. 23:Monthly energy purchased and sold to the grid

The energy performance analysis shows the monthly energy purchased and sold to the grid, demonstrating that the system is capable of offsetting grid consumption, with some months showing net energy export. The figure further illustrates the energy purchased and sold throughout the year, highlighting periods of higher solar generation. The system achieves a total net present cost (NPC) of $3,194.20, a low levelized cost of energy (LCOE) of $0.02786/kWh, and an annual operating cost of $29.50, indicating its economic feasibility and potential for long-term savings.

5.8 Bidirectional Power Flow Challenges in Solar Home Systems with Grid Integration

The integration of solar home systems (SHS) into the grid introduces bidirectional power flow challenges, as energy can flow both from the grid to the consumer and from the consumer to the grid. This bidirectional nature, while beneficial for energy efficiency and grid support, also presents technical and operational challenges that must be addressed for stable and reliable power system operation. bidirectional power flow introduces technical issues such as voltage instability, reverse power flow complications, harmonic distortion, frequency fluctuations.

5.8.1 Voltage Fluctuations and Stability Issues

Traditional power grids are designed for unidirectional power flow, where electricity flows from centralized power plants to consumers. However, with the integration of multiple SHS, excess solar energy generated during peak sunlight hours is injected into the grid, leading to voltage fluctuations.

During periods of high solar generation, localized voltage rises above nominal levels, potentially exceeding grid voltage limits. Conversely, during low solar generation or high demand, voltage drops, affecting sensitive equipment and grid reliability. To mitigate voltage instability, advanced voltage regulation techniques such as on-load tap changers (OLTCs), reactive power compensation from inverters, and smart grid solutions can be implemented.

5.8.2 Reverse Power Flow Impact on Transformers and Protection Systems

In conventional distribution networks, power flows from high-voltage transmission systems to low-voltage consumers. However, with SHS integration, reverse power flow occurs when surplus solar energy is exported to the grid. This reverse power flow can overload distribution transformers, reducing their lifespan and increasing thermal stress. Protection systems, such as overcurrent relays and fuses, are designed for unidirectional flow and may fail to detect faults properly in a bidirectional scenario.

To address these issues, adaptive protection schemes, directional relays, and advanced transformer designs are required to accommodate bidirectional flows safely.

5.8.3 Harmonic Distortion Due to Power Electronics

Most SHS use power electronic inverters to convert DC power from solar panels to AC power for household and grid use. However, these inverters introduce harmonic distortion, leading to power quality issues. Harmonics can cause equipment overheating, increased losses, and malfunctioning of sensitive electronic devices. The interaction of multiple SHS inverters can lead to resonance conditions, further exacerbating harmonic problems. To mitigate harmonic distortion, filtering techniques, improved inverter control strategies, and grid compliance regulations.

5.8.4 Frequency Stability and Grid Synchronization

Unlike conventional generators, solar home systems do not provide inertia to the grid. This results in frequency instability, especially when a large number of SHS units are integrated. The Sudden variations in solar irradiance (e.g., due to passing clouds) can cause rapid changes in power injection, leading to frequency deviations.

Improper synchronization of multiple SHS inverters with the grid can lead to islanding issues, where SHS continue to supply power to a disconnected section of the grid, posing a safety risk.

5.8.5 Analysis on grid compatibility

Grid compatibility of Solar Home System (SHS) integration was assessed using an 8760-hour quasi-static power-flow model with real network data and HOMER-generated PV/battery profiles. Various penetration levels and inverter control modes were tested per IEEE 1547 and national standards. The study analyzed technical impacts like voltage deviations, thermal overloads, losses, and harmonics. Hosting-capacity limits were identified, and mitigation strategies such as inverter controls and grid upgrades were evaluated for improved compatibility. The evaluation revealed that before SHS integration, the grid maintained acceptable voltage, frequency, and power quality levels. However, following integration particularly at high penetration technical challenges arose, including reverse power flow, voltage rise, increased on-load tap changer (OLTC) operations, and protection coordination issues. Incorporating SHS with battery storage and advanced inverter functions effectively mitigated these problems, enhancing hosting capacity and voltage stability. Although SHS reduced household reliance on the grid and improved reliability, they also introduced new operational complexities, underscoring the need for robust control strategies, system upgrades, and regulatory compliance to ensure sustained grid performance.

5.9 Interpretation of results.

The results from the simulation indicate that integrating a Solar Home System into the power grid is both technically and economically feasible. The SHS produced a significant portion of the household's energy needs and provided a reliable backup during periods of low solar generation. The grid interaction was minimal, and excess energy produced was successfully exported to the grid, benefiting both the homeowner and the local grid. The economic analysis showed that the system is a good investment, with a reasonable payback period. The environmental impact, including significant CO2 reduction, highlights the contribution of the SHS to sustainability efforts.

However, the project's financial feasibility is sensitive to variations in solar irradiance, electricity tariffs, and battery storage capacities. The Excess power injected into the grid can exceed the local demand, overloading the distribution lines and transformers.

Without proper energy storage and demand response mechanisms, this excess energy may be curtailed, reducing the economic benefits of SHS owners. To manage bidirectional flows efficiently, the integration of battery energy storage systems (BESS) is necessary.

5.10 The Current Situation After Integrating SHS to Power Grid

After integrating Solar Home Systems (SHS) into the national grid, several improvements were observed in energy availability, reliability, and reduced reliance on diesel or expensive backup systems. The grid integration enabled excess solar generation during peak sunlight hours to be injected into the grid, improving overall energy stability in rural areas. Households benefited from improved service continuity, especially during cloudy periods or at night, when the grid could supplement SHS limitations. Voltage profiles stabilized, and system losses were minimized through efficient inverter operation and battery backup. The figure 6. 1 depicts monthly energy purchased and sold to the grid and the system achieves a total net present cost (NPC) of $3,194.20, a low levelized cost of energy (LCOE) of $0.02786/kWh, and an annual operating cost of $29.50, indicating its economic feasibility and potential for long-term savings. The table4. describe the comparison aspect before and after integration of SHS to the grid.

Table 5. 2:Comparison Analysis Before and after SHS integration

Aspect	**Before (Standalone SHS)**	**After Integration (Grid-tied SHS)**
Supply	Local only; limited by panel & battery	Grid + local PV; export/import possible
Reliability	Depends on battery state/maintenance	Higher with grid backup; even higher if utility can coordinate batteries during peaks/outages
Voltage/Protection	No feeder interaction	Needs voltage control, anti-islanding, updated protection settings
Metering	Single internal SHS meter	Bi-directional or smart meter; export credited via policy (net metering/billing)
Utility Operations	Not visible to the Distribution System Operator	Visible Distributed Energy Resources (DERs) requiring hosting-capacity studies, possible curtailment/dispatch
Economics	User avoids bills but faces battery cost	Bills depend on tariff + export rate; network cost recovery needs careful design
Policy Needs	Product/quality standards	Interconnection rules, safety, cyber/telemetry, fair export pricing

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study evaluated the feasibility of integrating Solar Home Systems (SHS) into the national electricity grid. The analysis demonstrated that SHS integration is technically feasible and can significantly enhance energy access, improve reliability, and support sustainability. However, technical challenges such as voltage rise, reverse power flow, increased losses, and protection coordination issues were identified at higher penetration levels. These challenges can be mitigated through advanced inverter functionalities (Volt/Var and Volt-Watt), battery storage, hosting-capacity assessments, and targeted network upgrades.

The study also confirms that integrating SHS with the national grid improves system reliability, maximizes solar energy utilization, and reduces power deficits in rural areas. Simulation results from HOMER show better load coverage and inverter utilization when connected to the grid compared to standalone systems. The incorporation of Solar Home Systems (SHS) with the grid utilizing Homer pro software marks a significant step toward improving energy access, sustainability, and dependability, especially in locations where conventional grid infrastructure is either absent or insufficient. SHS can help mitigate energy deficits, reduce reliance on fossil fuels, and promote cleaner, renewable energy sources. With advancements in technology, decreasing costs of solar panels, and innovative grid integration methods.

With PV systems connected to the grid, the voltage profile across the busbars was dynamic, with the solar generation playing a crucial role in voltage regulation. Dig SILENT Power Factory simulate these conditions, assess the impact of each PV system, and optimize voltage control strategies to ensure system stability and efficiency. Overall, SHS-grid integration has the potential to accelerate rural electrification, diversify energy supply, and contribute to Rwanda's commitments toward climate change mitigation

6.2 Recommendations

The Governments should develop clear and supportive policies and regulations for integrating Solar Home Systems into the grid. This includes incentives for renewable energy adoption, grid-connection standards, and fair compensation for energy producers. This Policies should also address grid stability and provide clear guidelines for distributed energy generation. Also, Collaboration between governments, private companies, international development organizations, and communities would be essential for the successful integration of SHS.

Integrating Solar Home Systems into the grid has the potential to increase energy access, enhance sustainability, and contribute to climate change mitigation. With the right policies, technological advancements, and collaborative efforts, the widespread integration of SHS can become a viable solution to meet the growing energy demands in underserved and rural areas. Policymakers should support SHS-grid hybrid systems through net metering policies and subsidies. As the feasibility results directly inform the policy, technical, and institutional measures recommended for successful SHS-grid integration, future studies should explore larger-scale microgrids incorporating community-level storage and dynamic pricing models.

REFERENCES

[1] J. Wang and W. Azam, “Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries,” *Geosci. Front.*, vol. 15, no. 2, p. 101757, 2024, doi: 10.1016/j.gsf.2023.101757.

[2] P. Li, “Annual Report 2022,” *AIMS Energy*, vol. 11, no. 1, pp. 135–139, 2023, doi: 10.3934/energy.2023007.

[3] Energy Development corporation limited, “a Concept Note on the Rwanda National Electrification Plan (Nep) -2022 Revision,” no. August, p. 13, 2022, [Online]. Available: https://www.reg.rw/fileadmin/user_upload/NEP_REVISION_CONCEPT_NOTE_2022.pdf

[4] V. Mergulhao, L. Capra, K. Voglitsis, and P. Parikh, “Rwandan Pay-As-You-Go Solar Home System User Payment Behavioural Types,” *2022 IEEE PES/IAS PowerAfrica, PowerAfrica 2022*, no. August, 2022, doi: 10.1109/PowerAfrica53997.2022.9905300.

[5] B. Soltowski, F. Stewart, S. Strachan, D. Campos-Gaona, O. Anaya-Lara, and S. Galloway, “A field trial of off-grid SHS Interconnection in Rwanda’s Northern Province,” *Energy Sustain. Dev.*, vol. 66, pp. 69–78, 2022, doi: 10.1016/j.esd.2021.11.004.

[6] L. Varnado and M. Sheehan, “Connecting to the Grid,” pp. 1–51, 2009, [Online]. Available: http://irecusa.org/wp-content/uploads/2009/11/Connecting-to-the-Grid-Guide-6th-edition.pdf

[7] Z. Dicka, E. Dolnikova, and D. Katunsky, “Solar architecture: Significance and integration of technologies,” *E3S Web Conf.*, vol. 550, 2024, doi: 10.1051/e3sconf/202455001002.

[8] J. Marchwiński and E. Lucchi, “Firmitas, Utilitas, and Venustas of photovoltaic architecture,” *Sol. Energy*, vol. 282, no. September, 2024, doi: 10.1016/j.solener.2024.112974.

[9] G. Cillari, F. Fantozzi, and A. Franco, “Passive solar solutions for buildings: Criteria and guidelines for a synergistic design,” *Appl. Sci.*, vol. 11, no. 1, pp. 1–19, 2021, doi: 10.3390/app11010376.

[10] S. Gao, “Sustainable Housing: Innovations and Challenges in Green Architecture,” *J. Lifestyle SDGs Rev.*, vol. 5, no. 5, p. e06598, 2025, doi: 10.47172/2965-730x.sdgsreview.v5.n05.pe06598.

[11] I. B. Golovanov, D. A. Tikhonov, and I. G. Tsygankova, “The RISM method for estimating hydrophobic intramolecular interactions between distant groups,” *Russ. J. Phys. Chem. A*, vol. 74, no. 5, pp. 763–766, 2000.

[12] S. Gupta, P. Gupta, P. Matapurkar, and V. Rajput, “Integration of Solar and Wind Energy :,” vol. 10, no. 3, pp. 605–609, 2023.

[13] P. Hajialigol, A. Moazami, and M. Aghaei, “Solar Energy System Integration for Energy

Transition: A Short Review from Technologies and Methods to Energy Management System and Challenges," *Sol. Radiat. - Enabling Technol. Recent Innov. Adv. Energy Transit. [Working Title]*, 2024, doi: 10.5772/intechopen.114956.

[14] E. R. Board, "SOCIO-ECONOMIC IMPACT OF SOLAR MINI-GRIDS IN ZAMBIA A comparative analysis of," no. 1, 2024.

[15] Z. Mirza and N. Gupta, "Integration of solar power to the electric grid: A case study," *Int. J. Eng. Sci. Technol.*, vol. 14, no. 3, pp. 74–84, 2022, doi: 10.4314/ijest.v14i3.9s.

[16] A. Nzahabwanimana, "REPUBLIC OF RWANDA MINISTRY OF INFRASTRUCTURE Kigali : July 2014," no. July, 2014.

[17] S. S. Panagoda *et al.*, "Advancements In Photovoltaic (Pv) Technology for Solar Energy Generation," *J. Res. Technol. Eng*, vol. 4, no. 3, pp. 30–72, 2023, [Online]. Available: https://www.researchgate.net/publication/372364724

[18] M. Khalid, "Smart grids and renewable energy systems: Perspectives and grid integration challenges," *Energy Strateg. Rev.*, vol. 51, no. June 2023, p. 101299, 2024, doi: 10.1016/j.esr.2024.101299.

[19] F. Report, O. N. National, and E. Strategy, "Design and Implementation of National Electrification Strategy (Nes) Final Report on National Electrification Strategy".

[20] Rwanda Energy Group, "Rwanda Electricity Distribution Master Plan," *June 2021 Revis.*, no. June, pp. 1–141, 2021, [Online]. Available: https://www.reg.rw/fileadmin/user_upload/Rwanda_Electricity_Distribution_Master_Plan.PDF

[21] M. Ag and N. Bolson, "Evaluation of Rwanda ' s Energy Resources Evaluation of Rwanda ' s Energy Resources," pp. 1–14, 2022.

[22] P. Carolyn. Roos, "Solar Electric System Design , Operation and Installation," *Washingt. State Univ. Ext. Energy Progr.*, no. October, p. 35, 2009, [Online]. Available: www.energy.wsu.edu

[23] NEA, "Understanding your solar PV system and maximising the benefits," pp. 1–12, 2020.

[24] S. Bhatti and A. Williams, "Estimation of surplus energy in off-grid solar home systems," *Renew. Energy Environ. Sustain.*, vol. 6, p. 25, 2021, doi: 10.1051/rees/2021024.

[25] V. Mahadevan, S. R. S, M. A. Rusho, and S. Yishak, "Critical review of energy storage systems: A comparative assessment of mechanisms, advantages, challenges, and integration with renewable energy," *Results Eng.*, vol. 26, no. February, 2025, doi: 10.1016/j.rineng.2025.105589.

[26] K. N. Nwaigwe, P. Mutabilwa, and E. Dintwa, "An overview of solar power (PV systems)

integration into electricity grids," *Mater. Sci. Energy Technol.*, vol. 2, no. 3, pp. 629–633, 2019, doi: 10.1016/j.mset.2019.07.002.

[27] A. P. Submitted, I. N. Partial, O. F. The, R. For, T. H. E. Degree, and N. Singh, "NON-CONVENTIONAL ENERGY SOURCES," 2009.

[28] M. I. Abdelwanis and M. I. Elmezain, "A comprehensive review of hybrid AC/DC networks: insights into system planning, energy management, control, and protection," *Neural Comput. Appl.*, vol. 36, no. 29, pp. 17961–17977, 2024, doi: 10.1007/s00521-024-10264-5.

[29] A. M. Saleh, V. István, M. A. Khan, M. Waseem, and A. N. Ali Ahmed, "Power system stability in the Era of energy Transition: Importance, Opportunities, Challenges, and future directions," *Energy Convers. Manag. X*, vol. 24, no. September, 2024, doi: 10.1016/j.ecmx.2024.100820.

[30] M. Shafiullah, S. D. Ahmed, and F. A. Al-Sulaiman, "Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review," *IEEE Access*, vol. 10, pp. 52233–52257, 2022, doi: 10.1109/ACCESS.2022.3174555.

[31] P. Kind, "Trends 2015 - IN PHOTOVOLTAIC APPLICATIONS Survey Report of Selected IEA Countries between 1992 and 2014," *Edison Electr. Inst.*, vol. 37, no. January, pp. 1–16, 2013, [Online]. Available: http://www.iea.org/Textbase/npsum/weo2010sum.pdf%5Cnwww.energywatchgroup.org%5Cnhttp://www.iea.org/publications/freepublications/publication/KeyWorld2014.pdf%5Cnhttp://www.iea-pvps.org/fileadmin/dam/public/report/technical/PVPS_report_-_A_Snapshot_of_Glob

[32] E. Man, "Control of Grid Connected PV Systems with Grid Support Functions," p. 119, 2012.

[33] P. Papechen and S. Sebastian, "A New RS Based Encryption Scheme for Wireless Communication," *Int. J. Innov. Res. Electr. Electron. Instrum. Control Eng.*, vol. 4, no. 7, pp. 2321–2004, 2016, doi: 10.17148/IJIREEICE.

[34] S. B. Masikana, G. Sharma, S. Sharma, and E. Çelik, "Frequency regulation in solar PV-powered thermal power system using FPA-PID controller through UPFC and RFB," *Electr. Eng.*, 2024, doi: 10.1007/s00202-024-02417-5.

[35] Purwanto, Hermawan, and Suherman, "Integration of Solar Energy Supply on the Smart Home Micro Grid to Support Efficient Electricity and Green Environment," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 239, no. 1, 2019, doi: 10.1088/1755-1315/239/1/012032.

[36] K. Babu, S. Sivasubramanian, C. S. Nivetha, R. Senthil Kumar, and M. Soundari, "Intelligent Energy Management System for Smart Grids Using Machine Learning Algorithms," *E3S Web Conf.*, vol. 387, 2023, doi: 10.1051/e3sconf/202338705004.

[37] A. Bislimi and A. Nikaj, "Analyzing Solar Energy Integration in Smart Grids with a Focus on Demand Response, Energy Management, and Grid Stability," no. October 2023, 2024.

[38] A. Dhenesh Raj and A. B. Agarwal, “Integration of Renewable Energy Sources in Buildings,” vol. 1, no. 3, pp. 50–55, 2014, [Online]. Available: http://www.krishisanskriti.org/jceet.html

[39] B. Harianto and M. Karjadi, “Planning of Photovoltaic (PV) Type Solar Power Plant as An Alternative Energy of the Future in Indonesia,” *ENDLESS Int. J. Futur. Stud.*, vol. 5, no. 2, pp. 182–195, 2022, doi: 10.54783/endlessjournal.v5i2.87.

[40] P. Rani, V. P. Arora, and N. K. Sharma, “An overview of integration of PV system into electric grid,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1228, no. 1, p. 012017, 2022, doi: 10.1088/1757-899x/1228/1/012017.

[41] D. Naoussi, S. Raoul, M. Reagan, and J. Jacques, “A Technical Analysis of a Grid-Connected Hybrid Renewable Energy System under Meteorological Constraints for a Timely Energy Management,” *Int. J. Smart grid*, no. V7i2, 2023, doi: 10.20508/ijsmartgrid.v7i2.278.g260.

[42] P. Rolffs, R. Byrne, and D. Ockwell, *Financing Sustainable Energy for All: Pay-as-you-go vs. traditional solar finance approaches in Kenya*, vol. STEPS Work, no. 59. 2014.

[43] A. Jacobson, “Connective Power: Solar Electrification and Social Change in Kenya,” *World Dev.*, vol. 35, no. 1, pp. 144–162, 2007, doi: 10.1016/j.worlddev.2006.10.001.

[44] P. A. Trotter, M. C. McManus, and R. Maconachie, “Electricity planning and implementation in sub-Saharan Africa: A systematic review,” *Renew. Sustain. Energy Rev.*, vol. 74, no. June 2016, pp. 1189–1209, 2017, doi: 10.1016/j.rser.2017.03.001.

[45] D. Henner and REN21, *Ren21*. 2017. [Online]. Available: https://abdn.pure.elsevier.com/en/en/researchoutput/ren21(5d1212f6-d863-45f7-8979-5f68a61e380e).html

[46] F. Balo and L. Şağbanşua, “The Selection of the Best Solar Panel for the Photovoltaic System Design by Using AHP,” *Energy Procedia*, vol. 100, no. November 2016, pp. 50–53, 2016, doi: 10.1016/j.egypro.2016.10.151.

[47] Natural Resources Canada, “Solar Ready Guidelines,” 2013, [Online]. Available: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/SolarReadyGuidelines_en.pdf

[48] R. Posorski, “Quality Standards for Solar Home Systems and Rural Health Power Supply,” no. February, pp. 13–73, 2000.

[49] “Lighting Global Quality Assurance Framework : Quality Standards & Test Methods”.

[50] IRENA, “Scaling Up Renewable Energy Deployment in Africa,” *Detail. Overv. Irena’S Engagem. Impact*, no. January, pp. 1–82, 2020, [Online]. Available: www.irena.org

[51] F. Frontini *et al.*, “IEA SHC Task 41: Solar enegy systems in architecture. Integration criteria

and guidelines (Part B),” p. 228, 2012.

[52] Ministry of Infrastructure, “Energy Sector Strategic Plan 2018/19 - 2023/24,” *Repub. Rwanda*, no. September, p. 29, 2018, [Online]. Available: https://www.mininfra.gov.rw/fileadmin/user_upload/infos/Final_ESSP.pdf

[53] A. K. S. David Tan, “Handbook for Solar Photovoltaic Systems,” *Energy Mark. Authority, Singapore Publ.*, pp. 4–9, 2011.

[54] N. F. Fabrice and BUCYEDUSENGE, “Rwanda Electricity Access Development Plan (2018-2024),” no. June 2022, 2024.

[55] C. Analysis, “Seminar_M.Tech.Seminar_IIT_Bombay_Semester1stpdf,” no. 10317014.

[56] M. Fabien, J. d. A. Niyonsaba, J. M. V. Bikorimana, and A. L. Kyaruzi, “Grid-connected photovoltaics prosumers to support smart city development in Rwanda: A case study for Ayabaraya Village,” *J. Energy Syst.*, vol. 7, no. 1, pp. 18–29, 2023, doi: 10.30521/jes.1086675.

[57] H. Gloria, H. Olivier, and I. M. Angella, “Contribution of solar energy for sustainable urban development in rwanda,” *Civ. Eng. Archit.*, vol. 7, no. 6, pp. 271–277, 2019, doi: 10.13189/cea.2019.070601.

[58] M. Asinyaka and J. Uwibambe, “Let there be light: Electrification of Rural Communities in Rwanda using Solar PV Systems,” *5th Int. Conf. Environ. Energy Dev.*, p. 22, 2018.

[59] ENTSO-E, “High Penetration of Power Electronic Interfaced Power Sources (HPoPEIPS),” no. March, p. 37, 2017.

[60] G. 09/32, “Grid Code Short Circuit Ratio requirement in respect of Very Large Synchronous Generating Units,” no. September, pp. 4–7, 2009.

[61] O. Damanik, O. C. Sakinci, G. Grdenic, and J. Beerten, “Evaluation of the use of short-circuit ratio as a system strength indicator in converter-dominated power systems,” *IEEE PES Innov. Smart Grid Technol. Conf. Eur.*, vol. 2022-Octob, 2022, doi: 10.1109/ISGT-Europe54678.2022.9960381.

[62] P. Kundur, “Power System Stability and Control - Prabha Kundur - McGraw-Hill Education,” 1994. [Online]. Available: https://www.mheducation.co.in/html/9780070635159.html

[63] “Ministerial_Guidelines_on_Minimum_standards_Requirements_for_Solar_Home_Systems_2022.pdf.”

[64] Ignace Gatare, “GUIDELINES N o 02 / GL / EL-EWS / RURA / 2019 ON MINIMUM TECHNICAL REQUIREMENTS FOR MINI-GRIDS IN RWANDA,” no. June, pp. 1–14, 2019.