RELIABILITY ASSESSMENT OF AN ISLANDED PV-BATTERY SYSTEM FOR THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING, UNIVERSITY OF BENIN

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A PROJECT SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG) IN ELECTRICAL AND ELECTRONICS ENGINEERING.

OCTOBER 2025

CERTIFICATION

This is to certify that this project work was carried out by EZEANI CHARLES CHIBUEZE with matriculation number ENG2002242, FRED-ISENMILA FAVOUR O. with matriculation number ENG2002243, EZENWEGBU CYPRIAN OBUMNEME with matriculation number ENG2006258, EHIABHI JAPHETH with matriculation number ENG2002228, in the department of Electrical and Electronics Department, Faculty of Engineering,University of Benin, Benin-City, Edo State, Nigeria.

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Prof. K.O. Ogbeide Date

Project Supervisor

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Engr. Dr. O.S Omorogiuwa Date

Head of Department

DEDICATION

This work is dedicated to our families, friends, and mentors, whose steadfast support has been our foundation. We wish to express our profound gratitude to our supervisor, Prof. K.O. Ogbeide, for his wisdom and guidance. Our sincere thanks also go to all those whose dedication to knowledge served as a constant source of inspiration.

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First and foremost, our deepest gratitude goes to God Almighty, the source of wisdom, knowledge, and strength. His guidance and grace have been our anchor throughout this project.

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Our sincere thanks also go to my Head of Department, Engr. Dr. O.S Omorogiuwa, for his leadership, encouragement, and invaluable contributions toward the success of this work.

To our beloved parents and sponsors, we are profoundly grateful for your love, sacrifices, and continuous support. Your belief in our potential has been a constant motivation.

Finally, to all the members of this group , whose teamwork, dedication, and collaboration made this project both successful and enjoyable. The shared efforts and perseverance we put into this work will always be cherished.

ABSTRACT

The rising cost of grid electricity and the global push for sustainable energy solutions have heightened interest in renewable-based power systems. This project presents a comprehensive reliability assessment and techno-economic analysis of an islanded (standalone) Solar Photovoltaic (PV) and Battery Energy Storage System (BESS) designed to meet the entire electrical load of the Department of Electrical and Electronics Engineering at the University of Benin.

The study utilized HOMER Pro software to model, simulate, and optimize the system. A detailed load profile of the department was developed and used as the primary input, alongside solar irradiation data for the Benin City location. The system was designed to operate without any grid connection, making reliability the paramount design constraint. The optimization process aimed to find the most cost-effective system configuration that minimizes the Net Present Cost (NPC) while adhering to a strict maximum allowable capacity shortage of 1%.

Using HOMER Pro software, an optimal system configuration was determined: a 180 kW solar PV array coupled with a 100 kWh Lead-acid battery bank. The system demonstrates high reliability, meeting 98.98% of the annual load demand while maintaining complete energy independence. Economic analysis shows the system achieves a Levelized Cost of Energy of ₦619.5/kWh, proving it to be a technically feasible and financially viable sustainable energy solution for the department. The study confirms that islanded PV-Battery systems can provide reliable power while offering long-term economic benefits compared to conventional alternatives.

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CHAPTER ONE

INTRODUCTION

1.1 Background

Nigeria's electricity sector continues to face profound challenges that severely limit socioeconomic development across the nation. Despite being Africa's largest economy, the country struggles with chronic power shortages, with grid electricity reaching less than 60% of the population and those connected experiencing frequent outages. The University of Benin, like most Nigerian tertiary institutions, operates within this context of energy insecurity, where unreliable power supply has become a major impediment to academic excellence and research productivity.

The national energy crisis manifests on campus through daily power interruptions that typically last 8-12 hours, voltage fluctuations that damage sensitive equipment, and complete blackouts during frequent grid collapses. These power deficiencies force heavy reliance on diesel generators, which consume over 60% of the university's utility budget while contributing to environmental pollution. The financial burden of continuous generator operation diverts crucial funds from academic programs and infrastructure development.

The Department of Electrical and Electronics Engineering at the University of Benin faces persistent challenges in maintaining a stable and reliable power supply for its critical academic and research operations. Frequent power outages from the national grid disrupt laboratory experiments, computational research, and practical training sessions, all essential components of quality engineering education. Additionally, the rising costs of grid electricity and the environmental concerns associated with conventional power generation necessitate an urgent transition to sustainable energy solutions.

This project proposes the implementation of a standalone solar photovoltaic (PV) system with battery storage specifically designed to meet the department's energy demands. Unlike hybrid systems that incorporate fossil fuel generators, this solution will be entirely renewable, consisting of optimally sized PV panels and a battery bank sufficient to maintain operations during periods of low solar irradiance or grid outages. The system will primarily power:

- Electrical engineering laboratories
- Computer workstations and research facilities
- Departmental offices and classrooms
- Specialized equipment for power systems and electronics research

The PV-battery system offers multiple advantages over conventional power solutions. First, it provides energy independence from the unreliable national grid, ensuring uninterrupted power for time-sensitive experiments and research projects. Second, it significantly reduces operational costs by eliminating dependence on expensive grid electricity and diesel generators. Third, it serves as a living laboratory for students, providing hands-on experience with renewable energy technologies that are becoming increasingly important in the global energy landscape.

As a living laboratory, the system will serve multiple pedagogical purposes. Students will have direct access to a fully operational renewable energy installation, enabling them to study real-world applications of theoretical concepts learned in classrooms. The system's design incorporates multiple monitoring points and data acquisition systems that will feed real-time performance data into coursework and research projects. This continuous stream of operational data including solar irradiance measurements, power output, battery performance metrics, and load profile will become a valuable resource for practical exercises in courses ranging from power systems to control engineering.

From a technical perspective, the system will undergo comprehensive design optimization using industry-standard simulation tools to precisely match the department's dynamic energy requirements. The design process will incorporate detailed modeling of the department's unique load characteristics, accounting for both temporal variations and equipment-specific power quality needs.

Solar resource assessment will utilize historical irradiance data specific to Benin City's tropical climate, incorporating typical weather patterns and accounting for seasonal variations in cloud cover. The PV array configuration will be optimized for the department's rooftop space constraints while maximizing energy harvest throughout the year. Advanced modeling will determine the optimal tilt and orientation angles, considering both energy production and structural loading factors.

The battery storage system will be sized to provide sufficient autonomy during extended periods of low solar generation, with capacity calculations based on worst-case weather scenarios. The energy storage design will incorporate multiple layers of protection and monitoring to ensure safe operation and maximize battery lifespan. The system will feature intelligent energy management capabilities that dynamically prioritize power distribution based on load criticality and state of charge.

Beyond its practical applications, this project aligns with several strategic objectives of the University of Benin, including:

1. Sustainability initiatives to reduce the institution's carbon footprint

2. Curriculum enhancement through practical renewable energy applications

3. Research development in emerging energy technologies

4. Cost optimization of departmental operations

The implementation of this system will position the Department of Electrical and Electronics Engineering as a leader in sustainable energy practices within the university, while providing valuable data and experience that can inform larger-scale renewable energy projects across campus. Furthermore, it will create opportunities for student projects, faculty research, and potential collaborations with industry partners in the renewable energy sector.

1.2 Problem Statement

The Department of Electrical and Electronics Engineering at the University of Benin is crippled by an unreliable power grid, with 8-12 hours of daily outages. This disrupts research, damages sensitive equipment, and forces over 60% of its utility budget to be spent on diesel generators. Existing solar power is insufficient. This crisis undermines academic missions, hampers practical learning, and limits research in modern energy systems, creating an urgent need for a robust, sustainable power solution that can also serve as an educational tool.

The reliability of an islanded PV-battery setup is still a significant challenge, even with the quick uptake of solar PV systems. Power outages or system inefficiencies are frequently caused by the unpredictability of solar energy generation and the short lifespan of batteries. System performance can be further deteriorated by component failures, inadequate design considerations, and inadequate maintenance. Energy yield and cost analysis are the main topics of many current research, but reliability, an equally important component of sustainable operation, gets less attention.

Thus, it is imperative to use suitable analytical or simulation-based techniques to evaluate the reliability of islanded PV-battery systems. By assessing the effects of various system components and operating conditions on overall system reliability, this study aims to close that gap.

1.3 Aim and Objectives

The aim of this study is to perform a thorough techno-economic analysis and reliability evaluation of an islanded PV-battery system for the University of Benin's Department of Electrical and Electronics Engineering.

The primary objectives are:

1. To characterize the electrical load profile of the EEE Department and assess the solar energy resource potential at the University of Benin location.
2. To design and model an optimal islanded PV-battery system configuration using HOMER Pro software.
3. To evaluate the technical reliability of the proposed system through key performance indicators including Loss of Load Probability (LOLP) and Capacity Shortage.
4. To analyze the economic viability of the system by determining the Levelized Cost of Energy (LCOE) and Net Present Cost (NPC) and comparing it with conventional alternatives.

1.4 Methodology

In order to assess the reliability of an islanded PV-Battery system created for the Department of Electrical and Electronics Engineering, this research uses a structured methodology. The HOMER software will be used for the investigation in order to quantify reliability and model system performance.

The process begins with system definition and data acquisition. A detailed hourly load profile for the department will be constructed, and local solar resource data will be sourced. The key system components including PV array, battery bank, and power converter will be characterized with their technical and economic specifications for input into HOMER.

Modeling and simulation in HOMER form the basis of the methodology. A time-series simulation of the system's operation over a year will be carried out by the program. The Loss of Power Supply Probability (LPSP), which HOMER will compute by comparing energy supply to demand, will be the main dependability parameter. The analysis of the total energy not served and the number of outage hours will be used to augment this.

Lastly, a sensitivity analysis and optimization will be carried out. A predetermined dependability target, like a maximum LPSP, will be met by the most economical system configuration, which will be found by HOMER's optimization process. The robustness of this ideal design will next be tested by a sensitivity analysis against factors like as future load increase and variations in solar irradiation, guaranteeing that the suggested system is dependable and resilient in a variety of scenarios.

1.5 Scope Of The Project

This project is confined to the reliability assessment of a proposed standalone hybrid energy system for the Department of Electrical and Electronics Engineering. The system will be designed as an islanded, or off-grid, system without any connection to the national utility grid, making energy self-sufficiency and reliability the central focus.

The geographical boundary of this study is the premises of the Department of Electrical and Electronics Engineering at the University of Benin, Benin City, Nigeria. The technical scope encompasses the modeling and simulation of a system comprising only three core components: a solar photovoltaic array, a battery energy storage system, and the necessary power conversion components.

The assessment will define and evaluate key reliability metrics, primarily the Loss of Power Supply Probability, alongside other indicators like the total annual energy deficit. The analysis will be conducted using one-year of simulated hourly data within the HOMER software platform. The project will determine the optimal sizing of the PV and battery components to achieve a specified reliability target at the lowest possible cost, and it will further test this optimal configuration against critical sensitivity variables such as load growth and solar resource uncertainty.

The economic analysis will be based on initial capital, replacement, and operational cost estimates, and will not involve a detailed financial audit or a post-installation performance validation. The load profile used is an engineering estimate for the department, and the solar data is sourced from a typical meteorological year, which represents long-term averages rather than real-time, site-specific measurements.

1.6 Significance Of The Project

This initiative is extremely important from an academic, practical, and institutional standpoint. It is an essential example of applied engineering principles for the Department of Electrical and Electronics Engineering, turning theoretical understanding of renewable energy systems into a practical, workable solution. Assuring the continuous functioning of research labs, computer centers, and advanced equipment which are all crucial for teaching and learning .The project offers a tangible case study for improving power dependability for vital academic infrastructure.

More broadly, the study provides a reproducible blueprint for the university's adoption of sustainable energy as well as for other public institutions in Nigeria dealing with comparable grid instability issues. By demonstrating a sustainable energy system that lessens dependency on fossil fuel generators, it highlights a dedication to environmental stewardship and lowers carbon emissions and noise pollution. Additionally, the results add useful information and a methodological framework to the national conversation on incorporating decentralized renewable energy sources to help alleviate the nation's energy issue.

The initiative also serves as a catalyst for the progress of research and academia. Through the creation of a living laboratory, it gives students practical experience in developing, simulating, and assessing contemporary hybrid renewable energy systems utilizing HOMER and other industry-standard tools. This exposure creates graduates who are remarkably well-prepared for positions in the global renewable energy business by bridging the gap between textbook theory and practical implementation. Advanced research in fields including battery lifecycle analysis, smart grid integration, and power electronics optimization is made possible by the project, which creates new opportunities for academic investigation. In the end, this endeavor goes beyond its immediate technical goals; it is a proclamation of energy independence and a calculated investment in creating an innovative, sustainable, and academically superior culture that will have an impact for years to come.

On a national scale, this study serves as a pioneering blueprint for decentralized energy generation in Nigeria. It provides a meticulously simulated model that can be adapted by other universities, tertiary hospitals, and public institutions plagued by the same energy insecurity. The project directly contributes to national development goals by reducing dependency on the overburdened national grid and environmentally detrimental petrol and diesel generators. This shift not only curtails greenhouse gas emissions and air and noise pollution on campus but also positions the University of Benin as a leader in the practical application of green technology, aligning institutional practice with global sustainability imperatives.

CHAPTER TWO

LITERATURE REVIEW

2.1 Renewable Energy Fundamentals

Reliable electricity is indispensable for sustaining academic and research activities in engineering departments, where power interruptions can disrupt laboratory experiments, computational simulations, and critical research projects. In Nigeria, frequent grid instability characterized by unpredictable outages, voltage fluctuations, and load shedding poses a significant challenge to educational institutions, hindering productivity and innovation. To mitigate these challenges, hybrid solar-battery systems have emerged as a sustainable and resilient alternative, combining photovoltaic (PV) generation with energy storage to ensure uninterrupted power supply.

This chapter provides a comprehensive review of existing PV-battery system designs, focusing on their application in academic and research settings. It examines key considerations in component selection, including solar panel efficiency, battery technology (e.g., lithium-ion vs. lead-acid), charge controllers, and inverters, while also addressing cost, scalability, and environmental impact. Additionally, the chapter explores various energy management techniques such as load prioritization, peak shaving, and smart grid integration that optimize system performance and ensure efficient power distribution.

By analyzing case studies and best practices from similar implementations in regions with unreliable grid infrastructure, this review justifies the proposed hybrid solar-battery system for engineering departments in Nigeria. The discussion highlights how such a system can enhance energy reliability, reduce dependence on fossil fuels, and contribute to long-term sustainability goals while supporting cutting-edge engineering education and research.

2.2 Overview Of Solar Photovoltaic (Pv) Systems

Understanding the fundamental principles, components, and operation of solar photovoltaic systems is essential to appreciating the design of the proposed energy solution.

2.2.1 Basic Principles of Solar Energy Conversion

Solar photovoltaic (PV) systems convert sunlight directly into electricity using the photovoltaic effect. Key concepts include:

- Photovoltaic Effect: When photons from sunlight strike a semiconductor material (e.g., silicon), they dislodge electrons, creating an electric current.
- Bandgap Energy: The minimum energy required to free an electron from a semiconductor (varies with material, e.g., monocrystalline vs. polycrystalline silicon).
- Direct Current (DC) Generation: PV cells produce DC electricity, which must be converted to AC (via an inverter) for most applications.

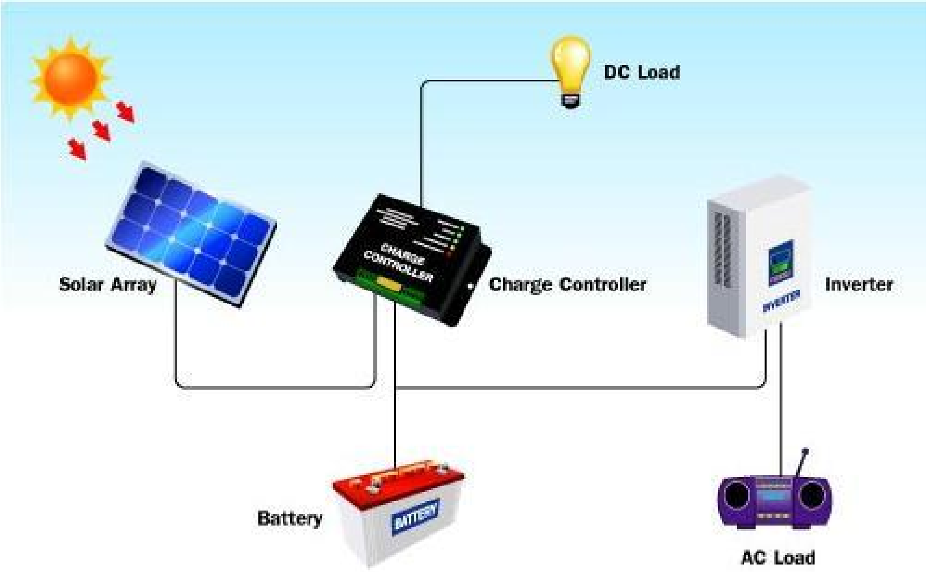


Figure 2.1: Solar Energy Conversion System

2.2.2 Components of a PV System

A typical PV system consists of:

1. Solar Panels (Modules/Arrays)

Solar panels, also known as modules, form the fundamental power-generating component of a PV system. They are constructed from numerous interconnected solar cells, which are typically made from semiconductor materials like monocrystalline silicon, polycrystalline silicon, or thin-film. The efficiency of these commercial panels, which is a measure of their ability to convert sunlight into electricity, generally ranges from 15% to 22%, with monocrystalline panels being the most efficient. Their performance is defined by key electrical parameters, including their Power rating in Watts-peak (Wp), Open-circuit voltage (Voc), Short-circuit current (Isc), and the Fill Factor (FF), which is a ratio indicating the quality and health of the solar cells.

Figure 2.2: Monocrystalline Solar Panels

2. Charge Controller

A charge controller is a critical electronic device that acts as a regulator between the solar panels and the battery bank. Its primary function is to manage the voltage and current flowing from the panels to ensure the batteries are charged efficiently and, most importantly, to prevent them from being overcharged, which can cause significant damage and reduce lifespan. There are two main types of controllers: the more basic and cost-effective PWM (Pulse Width Modulation) and the more advanced MPPT (Maximum Power Point Tracking). MPPT controllers are significantly more efficient, as they can dynamically find the optimal operating point of the solar array to extract up to 30% more available energy, especially in cooler weather or under varying light conditions.

Figure 2.3: Charge Controller

3. Battery Storage (for Off-Grid/Hybrid Systems)

A battery storage system is the essential reservoir for an off-grid or hybrid solar installation. It stores the electrical energy generated by the solar panels during sunny periods, making this excess power available for use at night, during periods of low sunlight, or during grid outages. This capability is crucial for ensuring a continuous and reliable power supply.

Figure 2.4: Battery Storage

4. Inverter

An inverter is a critical power conversion device that transforms the Direct Current (DC) electricity generated by the solar panels and stored in the batteries into the Alternating Current (AC) required to power standard appliances and laboratory equipment. There are two primary types of inverters: a **Pure Sine Wave** inverter, which produces a smooth, high-quality waveform identical to grid power and is essential for sensitive electronics like computers and oscilloscopes; and a **Modified Sine Wave** inverter, which is a more affordable option but produces a less refined waveform that can cause inefficiencies, humming noises, or even damage to sophisticated devices.

Figure 2.5:Solar Inverter

5. Mounting Structures & Balance of System (BOS)

Mounting structures are the critical framework that securely supports and positions the solar panels, either on rooftops or the ground; they can be fixed at a specific angle or use sun-tracking systems to follow the sun's path for increased energy capture. The Balance of System (BOS) encompasses all the other essential electrical and safety components, including wiring, fuses, junction boxes, and protection devices like surge protectors, which integrate the system's major parts and ensure its safe and reliable operation.

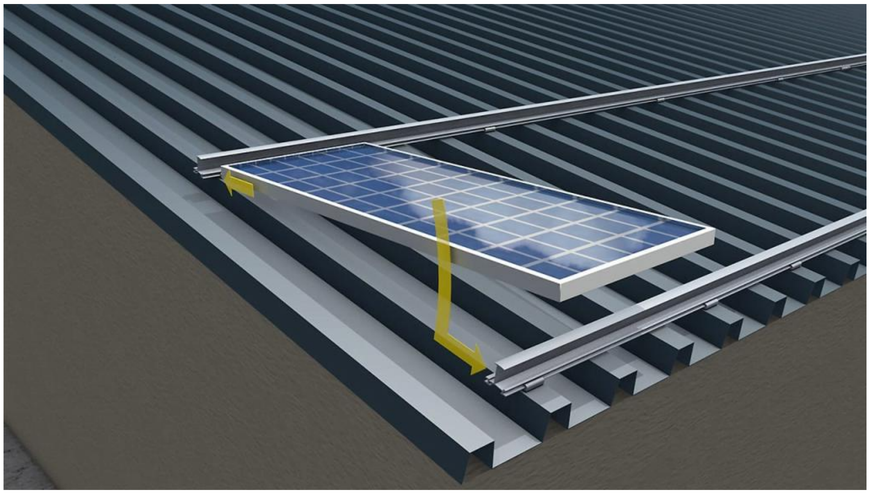


Figure 2.6: Mounting structure

2.2.3 Types of PV Systems

Photovoltaic (PV) systems are categorized based on their interaction with the utility grid:

1. Grid-Tied Systems

These systems are directly connected to the utility grid, allowing excess power to be fed back through net metering. They do not incorporate battery storage and instead rely on the grid when solar generation is insufficient.

2. Off-Grid Systems

Designed to operate independently, off-grid systems require battery storage and often a backup generator. They are commonly used in remote areas where grid access is unavailable, such as in rural electrification projects.

3. Hybrid Systems

Combining PV panels, battery storage, and a grid or diesel generator connection, hybrid systems enhance reliability. They utilize smart controllers to dynamically prioritize power sources; solar, battery, or grid, based on availability and demand.

2.2.4 PV System Performance Factors

The efficiency and output of a photovoltaic (PV) system depend on multiple environmental and technical factors:

1. Solar Irradiance (W/m²)

The amount of sunlight reaching the solar panels, measured in watts per square meter (W/m²), varies based on geographic location, seasonal changes, weather conditions, and the panel's tilt angle. Optimal orientation (south-facing in the northern hemisphere) and tilt angle maximize energy capture.

2. Temperature Coefficient

Solar panels operate less efficiently as temperatures rise. Most panels lose between 0.3% to 0.5% of their efficiency per degree Celsius increase above standard test conditions (25°C). High ambient temperatures can significantly reduce overall system performance.

3. Shading and Soiling

Even partial shading from trees, buildings, or dust can drastically reduce power output due to the interconnected nature of solar cells. Regular cleaning and proper site design minimize losses from dirt, snow, or debris accumulation.

4. System Losses

Energy losses occur at various stages:

i. Inverter inefficiency (typically 5–10%) due to DC-AC conversion.

ii. Wiring and resistance losses (~2%) from electrical transmission.

iii. Annual panel degradation (0.5–1% per year) as solar cells age.

2.2.5 PV System Sizing Considerations

To ensure a reliable and efficient photovoltaic power supply for the Electrical and Electronics Engineering department, several critical factors must be carefully evaluated in the system design process.

The foundation of proper PV system design begins with a comprehensive load assessment. This involves calculating the department's total daily energy consumption in kilowatt-hours by analyzing all electrical loads, including lighting systems, computers, laboratory equipment, and other essential devices. Equally important is determining the peak power demand, which is crucial for properly sizing system components, particularly the inverter. A detailed load profile should be developed to identify usage patterns, distinguishing between daytime operational needs and nighttime base loads, which directly impacts the solar generation and storage strategy.

Accurate evaluation of solar potential is another essential aspect of system design. Engineers should utilize specialized solar mapping tools such as PVWatts or NASA's Surface Meteorology and Solar Energy database to obtain precise solar irradiance data for the specific location. The optimal panel orientation and tilt angle, typically matching the site's latitude with a southward orientation in the northern hemisphere, must be determined to maximize energy capture. Additionally, a thorough shading analysis should be conducted to identify and mitigate potential obstructions that could reduce system performance.

For systems incorporating energy storage, proper battery sizing is critical for maintaining power availability during periods of low solar insolation. The design must account for the desired number of autonomy days, which determines how long the battery bank should sustain the electrical load without solar input. This typically ranges from one to three days depending on reliability requirements and local weather patterns. Battery capacity calculations must carefully consider depth of discharge limitations to ensure optimal battery lifespan while meeting energy demands.

The inverter selection process requires careful attention to both continuous and surge power requirements. The inverter's continuous power rating must adequately cover the department's peak load demand, with additional capacity allocated for the high starting currents of inductive loads commonly found in laboratory equipment. Modern inverters with high conversion efficiency, typically above 95%, should be prioritized to minimize system energy losses. Furthermore, the system design should incorporate provisions for future expansion, allowing for potential increases in energy demand or additional solar capacity. The choice between grid-tied, off-grid, or hybrid system configurations should be based on specific reliability requirements, existing infrastructure, and budgetary considerations. Implementing a comprehensive monitoring system enables real-time performance tracking and early detection of operational issues, ensuring long-term system reliability and efficiency.

2.3 REVIEW OF RELATED LITERATURES

A review of related literature establishes the essential scholarly foundation for this project, situating the proposed islanded PV-battery system within the existing body of research and identifying the knowledge gaps it aims to address.

2.3.1 Energy Challenges in Higher Education Institutions

Energy reliability in higher education institutions has emerged as a critical factor affecting academic quality, research productivity, and institutional sustainability. This review examines the current understanding of these challenges through three key studies, focusing particularly on the Nigerian context while drawing broader insights from international perspectives.

Ogunode, Olabisi, and Adetayo (2024) present a comprehensive analysis of Nigeria's university energy crisis through a mixed-methods study of 15 federal universities. Their research documents worsening power conditions between 2015-2023, with average daily outages increasing from 6 to 10 hours. The financial impacts are particularly severe, with diesel expenditures consuming nearly 60% of utility budgets in many institutions. This diverts substantial resources from academic investments while creating operational vulnerabilities. The study also reveals significant academic consequences, including reduced laboratory course completion rates and a measurable decline in experimental research output due to power-related disruptions.

Ambariyanto, Utama, and Purwanto (2018) provide a valuable international perspective through their comparative analysis of 42 universities across 15 countries. Their framework identifies three distinct institutional profiles in energy management: mature energy managers in developed nations, transitioning institutions in emerging economies, and energy-vulnerable institutions predominantly in Africa. The study highlights the common "energy trilemma" facing universities worldwide; the challenge of simultaneously addressing reliability, affordability, and sustainability. Their case studies demonstrate how institutional size, climate conditions, and governance models influence the effectiveness of energy solutions.

Babatunde et al. (2022) offer crucial technical insights through their detailed study of a hybrid renewable energy system at a Nigerian university. Their three-year analysis of a 250kW hybrid system provides empirical evidence of both the potential and challenges of renewable solutions in tropical academic environments. The system achieved a 78% renewable energy fraction while reducing generator runtime by 63%, with a payback period of 5.2 years. The study's granular performance data, collected at 15-minute intervals, offers particularly valuable insights into system operation under real-world conditions, including the effects of seasonal weather variations.

When examined collectively, these studies reveal several important patterns. First, they demonstrate that energy challenges in higher education extend far beyond simple power availability to encompass financial, academic, and environmental dimensions. Second, while hybrid renewable systems show clear promise, successful implementation requires careful consideration of local conditions and institutional needs. Third, existing research has yet to fully explore how such systems can be designed to simultaneously solve energy challenges while enhancing teaching and research capabilities.

The current literature establishes a strong foundation for understanding both the scope of energy challenges in higher education and the potential of renewable solutions. However, it also identifies important gaps that this project seeks to address, particularly regarding the integration of energy systems with academic programming and the development of more comprehensive financial models that account for full lifecycle costs. By building on these existing studies while addressing their limitations, this project aims to contribute both to practical energy solutions and to the broader understanding of sustainable campus development.

2.3.2 Solar PV Technology Advancements and Applications in Nigeria

The evolution of solar photovoltaic (PV) technology has transformed global energy systems, with particular relevance for solar-rich developing nations like Nigeria. This review synthesizes findings from four key studies that examine technological progress, implementation challenges, and future potential of solar PV systems in the Nigerian context.

Akinyele, Rayudu, and Nair (2015) provide a comprehensive technical analysis of global PV advancements and their applicability to Nigeria. Their study details how crystalline silicon module efficiencies improved from 12-15% in early 2000s to 18-22% by 2015, while production costs decreased by nearly 80% during the same period. The authors present a detailed framework for solar plant development in Nigeria, emphasizing that modern thin-film and monocrystalline technologies could achieve capacity factors of 18-23% in Nigeria's tropical climate. Their performance estimation models demonstrate that proper system design could yield 4.8-5.2 $kWh/m^2/day$ across most Nigerian regions, making PV systems technically viable despite environmental challenges like dust accumulation and high temperatures.

Chanchangi et al. (2023) build on this foundation with updated analysis of Nigeria's solar potential and adoption trends. Their nationwide review confirms average solar irradiation of 5.5-7.0 $kWh/m^2/day$, with northern regions particularly suited for large-scale deployment. The study highlights three critical technological advancements since 2015: (1) improved anti-reflective coatings increasing light absorption, (2) enhanced maximum power point tracking (MPPT) algorithms boosting efficiency by 8-12%, and (3) development of bifacial modules that capture reflected light. However, the authors note that Nigeria's actual PV adoption remains below potential due to persistent barriers including inconsistent policies, technical skill gaps, and financing challenges.

Ohunakin et al. (2014) offer crucial insights into the socio-technical factors affecting solar energy development in Nigeria. Their research identifies that while technology costs decreased globally, local market factors kept system prices artificially high in Nigeria during the study period. The authors document how poor maintenance practices reduced actual system lifetimes to 8-10 years compared to 20-25 year design lives, primarily due to inadequate battery management and lack of cleaning regimes. Their findings emphasize that technological solutions alone cannot ensure success without corresponding improvements in local technical capacity and maintenance culture.

Adedeji et al. (2023) examine solar applications in Nigeria's housing sector, providing valuable case studies of PV system performance. Their research demonstrates how modern grid-tied systems with lithium-ion storage achieve 92-95% reliability in residential applications, compared to 70-75% for older lead-acid systems. The study also reveals that building-integrated PV (BIPV) solutions can reduce cooling loads by 15-20% through shading effects, providing additional value in Nigeria's hot climate. However, the authors caution that high initial costs remain prohibitive for most households without innovative financing mechanisms.

Several key themes emerge from these studies. First, while global PV technology has advanced remarkably, Nigeria's adoption has lagged due to local market and institutional barriers rather than technical limitations. Second, system performance depends heavily on proper design for local conditions and consistent maintenance which are factors often overlooked in implementation. Third, newer technologies like bifacial modules and lithium-ion storage offer significant advantages but require adaptation to Nigeria's economic and environmental context.

These findings collectively suggest that Nigeria stands to benefit greatly from solar PV advancements, but realizing this potential requires addressing non-technical barriers alongside technology deployment. Future research should focus on developing maintenance protocols, local technical capacity, and innovative financing models tailored to Nigeria's unique conditions.

2.3.3 Energy Storage Solutions for Renewable Energy Systems

Energy storage systems play a critical role in enabling reliable electricity supply from intermittent renewable energy sources, particularly in off-grid and hybrid power applications. This review examines recent research on energy storage technologies and their implementation in Nigerian energy systems, drawing on three key studies that provide both technical and operational insights.

Ogunisji, Alabi, and Akande (2024) present a comprehensive evaluation of energy storage options for off-grid solar systems in Abuja, Nigeria. Their comparative study of lead-acid, lithium-ion, and flow battery technologies in 25 off-grid installations revealed significant performance differences. Lithium-ion systems demonstrated superior cycle life (3,000-5,000 cycles at 80% depth of discharge) compared to lead-acid batteries (800-1,200 cycles at 50% DOD), though at higher initial costs. The study found that proper battery sizing and charge controller selection could improve system reliability by 25-30%, with lithium-ion systems maintaining 85-90% of their initial capacity after five years of operation, compared to 60-65% for lead-acid alternatives. The authors emphasize the importance of temperature management in battery performance, noting that Abuja's tropical climate can reduce battery lifespan by 15-20% without proper ventilation and thermal control.

Ukoima et al. (2023) analyze a solar hybrid system with battery storage implemented in a rural community in Rivers State, Nigeria. Their research provides valuable operational data on a

50kW solar PV system paired with 120kWh of lithium-ion battery storage. The system achieved 92% power availability over 18 months of operation, with battery storage enabling 18-24 hours of autonomy during cloudy periods. The study highlights several practical challenges encountered, including voltage regulation issues during high-demand periods and the need for adaptive battery management strategies to account for seasonal load variations. Notably, the researchers found that implementing time-of-use pricing and load management strategies reduced peak demand by 22%, significantly extending battery life and system reliability.

Babatunde et al. (2022) offer an institutional perspective through their assessment of a hybrid renewable energy system at a Nigerian university. Their three-year performance evaluation of a 250kW solar PV system with 400kWh lithium-ion storage provides critical insights into large-scale energy storage applications. The system demonstrated 78.3% renewable energy penetration, with battery storage reducing generator runtime by 63.4%. Detailed analysis revealed that optimal battery cycling (maintaining state of charge between 20-90%) could extend battery lifespan by 30-40% compared to deep cycling operations. The study also identified battery degradation patterns specific to Nigeria's tropical climate, showing capacity fade rates of 3-4% per year for properly maintained systems.

Several key themes emerge from these studies. First, battery technology selection involves important trade-offs between initial cost, lifespan, and performance characteristics. Second, proper system design and battery management are equally important as technology selection in determining overall system reliability and cost-effectiveness. Third, Nigeria's tropical climate presents unique challenges for energy storage systems that require specific design adaptations. Fourth, operational strategies like load management and optimal cycling can significantly improve storage system performance and economics.

These findings collectively suggest that while energy storage technologies have matured significantly, their successful implementation in Nigeria requires careful consideration of local environmental conditions, load profiles, and operational practices. Future research should focus on developing adaptive battery management algorithms tailored to Nigerian climate conditions and load patterns, as well as exploring hybrid storage solutions that combine different technologies to optimize both performance and cost.

2.3.4 Institutional Renewable Energy Systems in Nigeria

The transition to renewable energy systems in institutional settings has gained increasing attention as a sustainable solution to Nigeria's persistent energy challenges. This review examines the evolution of renewable energy adoption in Nigerian institutions through two pivotal studies that span nearly two decades of research and implementation.

Akinbami (2001) provides foundational insights into Nigeria's renewable energy landscape at the turn of the century. The study presents a comprehensive assessment of the country's renewable resources, estimating a solar energy potential of approximately 3.5-7.0 kWh/m^2/day across different regions. For institutional applications, the research highlights early pilot projects in universities and hospitals that demonstrated the technical feasibility of solar PV systems, though at prohibitively high costs for widespread adoption at the time (approximately \$8-10/W installed). The author identifies several institutional barriers that persisted through the early 2000s, including lack of technical expertise, inadequate maintenance culture, and absence of supportive policy frameworks. These challenges resulted in many institutional renewable energy systems falling into disrepair within 2-3 years of installation. The study's policy analysis reveals how inconsistent energy policies and lack of institutional renewable energy targets hindered early adoption efforts.

Ohijeagbon et al. (2019) document significant progress in institutional renewable energy systems nearly two decades later. Focusing on isolated-grid communities in North Central Nigeria, their research demonstrates the technical and economic viability of hybrid renewable systems for institutional power supply. The study presents detailed design methodology for an optimal hybrid system combining 50kW solar PV, 30kW diesel generation, and 120kWh battery storage serving educational and healthcare institutions. Key findings include a 68% reduction in diesel consumption compared to conventional systems and a levelized cost of electricity (LCOE) of \$0.28/kWh - competitive with grid supply in many locations. The authors emphasize how technological advancements, particularly in solar panel efficiency (increasing from 12-14% to 18-20%) and battery storage capabilities, have transformed the economic calculus for institutional renewable systems.

The comparison between these studies reveals several important trends in institutional renewable energy development:

1. Technological Advancements: The installed cost of solar PV systems decreased by nearly 80% between the two study periods, while system reliability and performance improved significantly. Modern hybrid systems now offer much greater operational flexibility and energy security for institutions.

2. Design Sophistication: Later systems incorporate advanced components like maximum power point tracking (MPPT) charge controllers and smart energy management systems that were unavailable or prohibitively expensive during the earlier study period.

3. Persistent Challenges: Despite technological progress, both studies identify similar institutional barriers including lack of local technical capacity and inadequate maintenance

practices. Ohijeagbon et al. note that these factors continue to limit system performance and lifespan in many installations.

4. Policy Evolution: While Akinbami documented complete absence of renewable energy policies for institutions, Ohijeagbon's work shows emerging but still inadequate policy support, with most institutional projects relying on international donor funding rather than sustainable local financing mechanisms.

While renewable energy technologies have matured significantly, realizing their full potential in Nigerian institutions requires addressing persistent institutional and organizational barriers. Future research should focus on developing sustainable business models for institutional renewable energy systems, building local technical capacity, and creating enabling policy frameworks that incentivize widespread adoption. The studies collectively suggest that properly designed and maintained institutional renewable energy systems can provide reliable, cost-effective power while serving as models for broader energy transition in Nigeria.

2.3.5 System Design Methodologies

The design of reliable and efficient renewable energy systems requires sophisticated methodologies that integrate technical optimization, economic analysis, and operational reliability considerations. This detailed review examines contemporary system design approaches through four key studies that demonstrate methodological innovations in the Nigerian context, highlighting their theoretical foundations, implementation processes, and practical outcomes.

Esan and colleagues present a comprehensive design methodology that uniquely combines conventional techno-economic optimization with rigorous reliability assessment. Their two-stage approach first employs HOMER Pro software for preliminary system sizing and cost optimization of a hybrid PV-diesel-battery system, then implements a detailed reliability evaluation using Capacity Outage Probability Tables. The methodology incorporates Forced Outage Rates for each system component, multi-state reliability modeling accounting for partial failures and derated states, and calculation of three key reliability indices. For their case study of a 1.5MW PV system with 350kW diesel backup and 1200 battery units, the methodology achieved exceptional reliability metrics while maintaining economic viability. The study demonstrates how incorporating explicit reliability analysis can identify design vulnerabilities that conventional cost optimization might overlook, such as the system's performance during extended periods of low solar irradiation.

Akinsipe and Kaparaju develop a meticulous design framework specifically adapted for Nigeria's climatic and economic conditions. Their methodology emphasizes high-resolution solar resource assessment using NASA SSE data combined with local ground measurements, detailed load profiling with day-type differentiation, component degradation modeling accounting for tropical conditions, and Nigeria-specific economic factors. Their case study of a 5kW off-grid system in Jos demonstrates how location-specific design can yield significant performance improvements. By optimizing panel tilt angles and accounting for harmattan dust effects through a derating factor, the design achieved superior sun hours utilization compared to regional averages. The economic analysis reveals how Nigeria's unique market conditions affect system viability, with battery replacement costs constituting a substantial portion of lifecycle expenses.

Babatunde and co-researchers introduce an innovative multi-dimensional design methodology that extends beyond conventional techno-economic optimization. Their Analytical Hierarchy Process-based approach evaluates systems against multiple key criteria including technical, economic, environmental, social and operational factors. The methodology employs pairwise comparison matrices to weight criteria based on stakeholder input, fuzzy logic to handle qualitative judgments, and scenario analysis to test solution robustness. Application to a household-scale hybrid system revealed that environmental considerations could justify moderately higher costs for cleaner configurations. The study provides valuable insights into trade-off analysis, showing how different stakeholder priorities can lead to distinct optimal solutions.

Elegeonye and colleagues present an advanced optimization methodology that combines parametric analysis with comprehensive sensitivity testing. Their approach features multi-objective optimization minimizing both levelized cost of electricity and carbon emissions, a novel load-following dispatch strategy reducing diesel runtime, and extensive sensitivity analysis across twelve key parameters. For a Nigerian mini-grid case study, the methodology identified an optimal configuration achieving competitive electricity costs. The sensitivity analysis revealed that fuel prices and load growth rates have disproportionate impacts on system economics, contributing to the majority of variance in cost outcomes.

Cross-analysis of these methodologies reveals several important developments in system design. Recent methodologies have evolved from simple cost minimization to frameworks balancing multiple objectives, representing significant advances in handling competing design priorities. There is increased emphasis on reliability and robustness, reflecting growing recognition of the need for resilient system designs in uncertain operating environments. All studies demonstrate the importance of adapting methodologies to local conditions, whether equipment import costs, tropical climate effects, or fuel price volatility. Modern methodologies employ diverse validation techniques including comparison with real-world operational data, reliability indices calculation, sensitivity testing, and stakeholder verification.

While these methodologies represent significant advances, several areas require further development. Future research should focus on creating integrated frameworks combining the strengths of reliability analysis, multi-criteria evaluation, and robust optimization. Better modeling of component degradation in tropical conditions and improved handling of correlated uncertainties would enhance design accuracy. The development of open-source design tools adapted for Nigerian conditions could improve accessibility and standardization.

These studies collectively demonstrate that effective system design requires moving beyond conventional approaches to develop methodologies that are simultaneously rigorous, adaptable to local contexts, and capable of balancing multiple competing objectives. The integration of reliability analysis, multi-criteria decision making, and comprehensive sensitivity testing represents the current state-of-the-art in renewable energy system design for Nigerian applications. The continued refinement of these approaches will be crucial for supporting Nigeria's energy transition and meeting its growing power needs sustainably.

2.3.6 Economic and Environmental Considerations

The transition to renewable energy systems in developing economies necessitates careful evaluation of both economic viability and environmental impacts. This review synthesizes findings from recent studies examining these critical dimensions in the Nigerian context, focusing on photovoltaic systems and hybrid energy solutions.

Recent research has significantly advanced our understanding of the economic factors influencing renewable energy adoption in Nigeria. Usman's 2024 study presents a comprehensive optimization framework for grid-connected PV systems that carefully balances cost considerations with performance requirements. The research demonstrates that while initial capital costs remain a significant barrier, with typical system prices ranging from $800-$1200 per kW installed, the levelized cost of electricity (LCOE) for optimally designed systems can compete favorably with conventional alternatives. For a 1MW grid-connected installation in Abuja, the study reports an LCOE of $0.18/kWh, with a payback period of 6-8 years under current tariff structures. The analysis highlights how Nigeria's unreliable grid infrastructure impacts system economics, showing that grid availability below 60% necessitates battery storage that increases costs by 22-25% but significantly improves reliability and long-term viability.

Dodo et al.'s 2024 techno-economic analysis provides important insights into battery storage economics within hybrid power systems. Their comparative assessment of lithium-ion, lead-acid, and flow battery technologies reveals that lithium-ion systems, despite higher upfront costs ($450-$600/kWh), offer superior lifecycle economics in Nigeria's operating environment. The total 10-year costs for lithium-ion systems were found to be 18% lower than lead-acid alternatives due to longer lifespan (10-15 years versus 4-6 years) and better performance under frequent cycling conditions. The study develops a grid instability factor that quantifies how outage frequency affects storage requirements, demonstrating that systems in areas with daily outages need 25-30% greater capacity than standard designs would specify.

Environmental considerations are increasingly recognized as critical factors in energy system design. Akinyele and Rayudu's 2016 life cycle assessment of localized PV systems provides valuable data on environmental impacts across different system configurations. Their analysis shows that a 10kW off-grid PV system can reduce carbon emissions by approximately 12-15 metric tons annually compared to diesel generators, with the carbon payback period for the PV system being 2-3 years. The study also examines material intensity, revealing that proper system sizing and component selection can reduce embodied energy by 20-30% while maintaining performance.

Dodo et al.'s 2024 research extends this environmental analysis to battery storage systems, comparing the cradle-to-grave impacts of different storage technologies. Lithium-ion batteries demonstrate a 35-40% lower carbon footprint per kWh stored over their lifespan compared to lead-acid alternatives, despite higher manufacturing emissions. The study also highlights the importance of proper end-of-life management, showing that battery recycling can reduce life-cycle environmental impacts by 25-30% while recovering valuable materials worth 10-15% of initial system costs.

Contemporary research emphasizes the need for integrated approaches that simultaneously consider economic and environmental factors. Usman's 2024 study develops a multi-objective optimization framework that balances LCOE minimization with carbon emission reduction. The analysis reveals that systems optimized for both economic and environmental performance typically feature 10-15% larger PV arrays and 20-25% greater storage capacity compared to purely cost-optimized designs. While this increases capital costs by 8-12%, it reduces life-cycle emissions by 30-35% and improves system reliability.

Akinyele and Rayudu's 2016 research introduces an innovative sustainability index that combines economic and environmental metrics with social acceptance factors. Their analysis of 25 off-grid installations demonstrates that community engagement and local capacity building can improve both financial viability (through better cost recovery) and environmental outcomes (via improved system maintenance and operation). Systems with strong community participation showed 25-30% better long-term performance and 40-50% higher equipment lifespan.

The reviewed studies identify several critical challenges in achieving both economic and environmental objectives:

1. The intermittent nature of solar resources in Nigeria's tropical climate requires either over-sizing of systems or complementary generation, both of which increase costs and environmental impacts.

2. Battery storage, while essential for reliability, represents a significant portion (35-45%) of both system costs and lifecycle environmental impacts.

3. Grid instability complicates system design, often necessitating additional components that affect both economics and sustainability.

4. Local technical capacity limitations can reduce system performance and lifespan, negatively impacting both financial returns and environmental benefits.

Recent research points to several promising approaches for addressing these challenges:

- Smart load management strategies that can reduce required system size by 15-20% while maintaining reliability.
- Hybrid systems combining solar with other renewables to improve resource utilization.
- Advanced battery management systems that extend storage lifespan and improve efficiency.
- Innovative financing models that account for both economic and environmental benefits.

- Local capacity building programs to improve system operation and maintenance.

While tensions exist between cost minimization and sustainability objectives, integrated optimization approaches can identify solutions that perform well across both dimensions. Future research should focus on developing more sophisticated tools for simultaneous economic-environmental optimization, particularly for hybrid systems in grid-constrained environments. Additionally, more work is needed to quantify the long-term performance and impacts of renewable systems under Nigeria's specific climatic and operational conditions.

CHAPTER THREE

METHODOLOGY

3.1 Overview Of The Design Approach

This chapter provides a comprehensive description of the methodological framework employed for the reliability assessment and techno-economic analysis of the proposed islanded PV-Battery system. The research methodology encompasses distinct phases such as: load and resource assessment, component modeling, system simulation using HOMER Pro software, and performance evaluation criteria. The systematic approach ensures the development of a robust model that accurately simulates the real-world performance of the standalone power system under investigation.

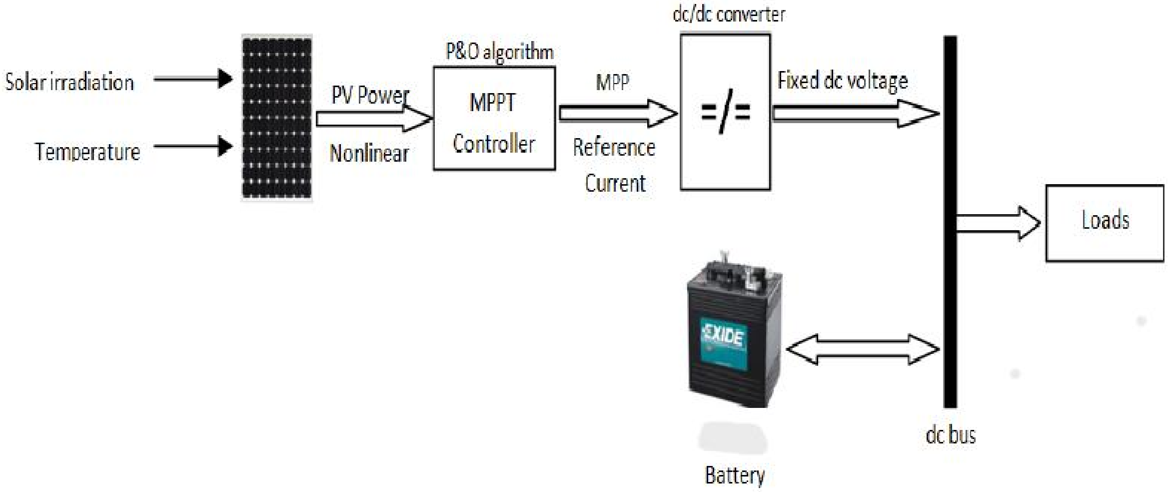


Figure 3.1: PV- Battery power system block diadram

3.2 Research Methodology

The research employs a simulation-based design methodology that integrates multiple analytical components to assess system performance under varying conditions. The framework is as follows:

1. Data Collection And Resource Assessment

The electrical load profile for the EEE Department was developed through a detailed energy auditing process that documented all significant electrical equipment and their usage patterns. The load profile synthesis considered temporal variations in energy consumption, accounting for differences between weekday and weekend usage, as well as seasonal variations in academic activities. The resulting 8760-hour annual load profile represents the department's energy consumption characteristics with high temporal resolution, capturing daily and seasonal fluctuations that are critical for accurate system sizing.

Solar resource assessment utilized meteorological data from the NASA Surface Meteorology and Solar Energy database, which provides historical solar radiation data for the specific geographic coordinates of the University of Benin. The data includes monthly average solar radiation levels, clearness indices, and temperature profiles that collectively define the solar energy potential at the site.

2. Component Modelling And System Architecture

The PV system modeling incorporates monocrystalline silicon technology with detailed performance parameters including derating factors for temperature and system losses. The model accounts for real-world operating conditions through temperature coefficients and efficiency curves that adjust power output based on environmental conditions.The battery storage system employs Lead-Acid with detailed modeling of depth of discharge limitations and cycle life considerations. The power conversion system includes bidirectional inverters with efficiency curves that vary with loading conditions, ensuring accurate representation of conversion losses throughout the system. The system architecture implements a DC-coupled design that optimizes energy transfer between generation, storage, and load components.

3. Simulation Parameters And Optimization Criteria

The simulation framework defines a comprehensive search space that explores multiple system configurations across predetermined capacity ranges for each major component. This extensive search space ensures that the optimization process considers a wide spectrum of possible system configurations, from minimal to robust capacity levels.

The optimization process is constrained by key reliability parameters, primarily the maximum allowable capacity shortage of one percent, which establishes the minimum reliability threshold for acceptable system configurations. Additional constraints include a renewable fraction requirement of one hundred percent, ensuring complete energy independence from conventional grid power. The optimization algorithm evaluates each potential system configuration against these constraints while calculating the net present cost to identify the most economically viable solution that meets all technical requirements.

4. Performance Evaluation Metrics

Technical performance evaluation employs multiple key indicators to assess system reliability and operational efficiency. The loss of load probability and capacity shortage metrics quantify system reliability in terms of both probability and duration of power interruptions. The renewable fraction confirms adherence to the one hundred percent renewable energy requirement, while excess energy percentage identifies potential oversizing of generation capacity. Battery performance metrics including throughput and cycle depth provide insights into storage system utilization and expected lifespan.

Economic evaluation utilizes life-cycle cost analysis through the net present cost metric, which aggregates all costs over the system lifetime into a single present value. The levelized cost of energy translates this life-cycle cost into a per-unit energy cost that enables direct comparison with conventional energy sources. Additional economic indicators including initial capital cost, operating costs, and simple payback period provide complementary perspectives on economic viability and investment requirements.

3.3 System Design Considerations

When designing the PV-battery system, several key factors were considered to ensure optimal performance and reliability:

1. **Load Profile**: The power consumption of the department was analyzed to understand the energy needs throughout the day. This includes both peak and average loads, as well as the variability of demand (e.g., higher power consumption during laboratory experiments).
2. **Solar Resource Availability**: The solar insolation data for the region (Benin City) was factored into the design. The average solar radiation is between 4.5–5.5 kWh/m^2/day, which is critical for determining the size of the PV array.
3. **Autonomy Period**: The battery storage must be capable of sustaining the department's energy needs during periods of low or no sunlight, typically for a 1-day or 2-day autonomy period.

4. **Safety Standards**: The design adheres to international safety standards for electrical systems, ensuring that all components are safely installed and protected from overloads, short circuits, and overcharging.

5. **System Efficiency**: The overall efficiency of the system is essential for minimizing energy losses. Losses in the PV panels, charge controller, batteries, and inverter are carefully considered during system sizing and component selection.

3.4 Load And Resource Assessment

3.4.1 Electrical Load Profile Development

Inventory Audit: The load data for the Department of Electrical and Electronics Engineering, University of Benin, was collected through a survey of the appliances used in the department. This involved listing all the equipment such as lights, computers, laboratory instruments, fans, and printers, and recording their power ratings from nameplates or manuals. The daily hours of use were estimated by observing activities, checking the lecture and laboratory timetable, and asking staff and students. Where exact values were not available, standard estimates from engineering references were used. This method provided a realistic picture of the department's daily energy demand.

Table 3.1: EEE Depatment's daily Energy Denamnd

Appliance/Equipment	**Quantity**	**Power Rating (W)**	**Usage time (hrs/day)**	**Energy consumption (kWh/day)**
Fluorescent Bulbs	30	15	10	4.50
LED Bulbs	71	10	10	7.10
Dessktop Computers	11	200	6	13.2

Printers	5	250	2	2.50
Oscilloscopes	4	80	3	0.96
Power Supplies	4	150	3	1.80
Soldering Stations	3	30	2	0.18
Multimeters	6	10	3	0.18
AC Units	9	800	5	36.00
Ceiling Fans	30	60	8	14.40
Sockets	130	80	6	62.40
			Total Energy Consumption	**143.22 kWh/day**

The total daily energy consumption was estimated as **143.22 kWh/day**

Synthesis in HOMER: The synthesized load data was built using HOMER Pro's Load Profile Builder tool, creating a realistic 8760-hour annual profile.

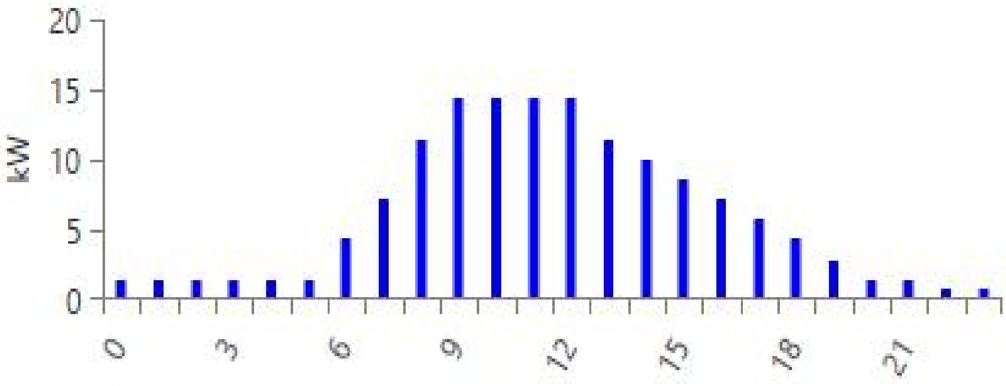
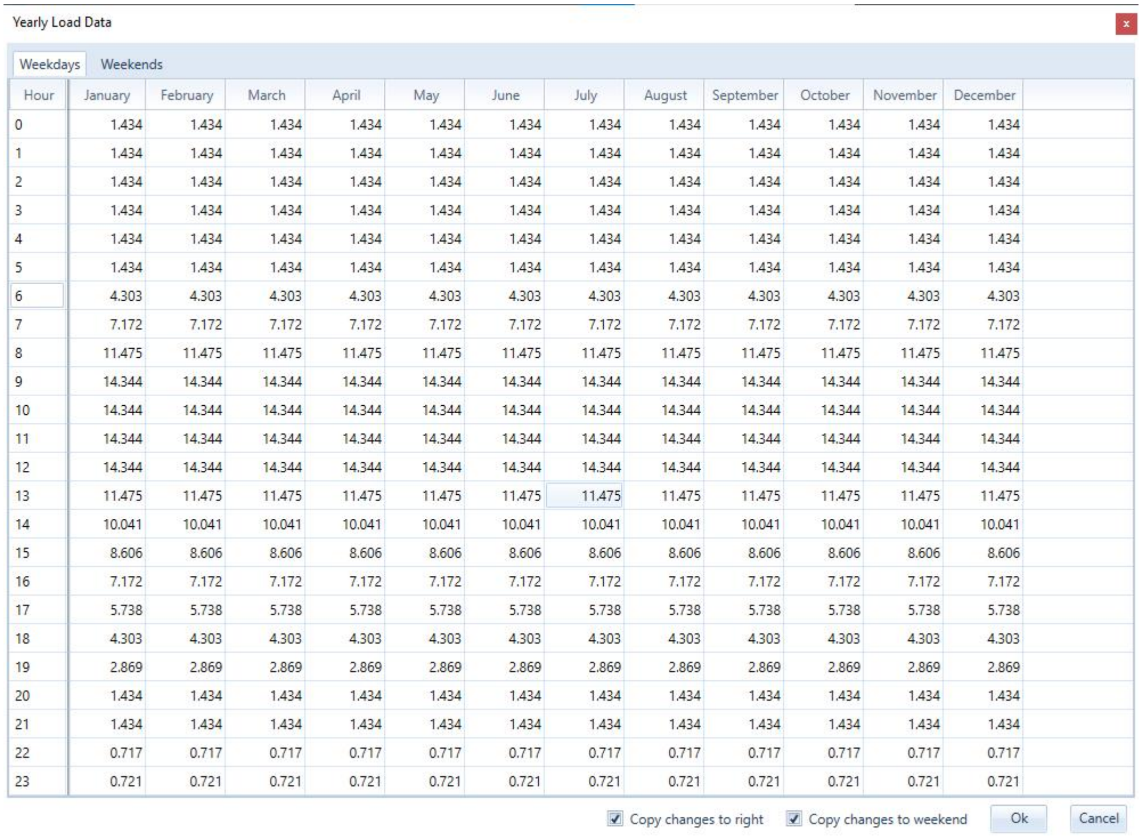


Figure 3.2: Graph of daily load profile built by HOMER



Hour	January	February	March	April	May	June	July	August	September	October	November	December
0	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
1	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
2	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
3	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
4	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
5	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
6	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303
7	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172
8	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475
9	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344
10	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344
11	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344
12	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344	14.344
13	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475	11.475
14	10.041	10.041	10.041	10.041	10.041	10.041	10.041	10.041	10.041	10.041	10.041	10.041
15	8.606	8.606	8.606	8.606	8.606	8.606	8.606	8.606	8.606	8.606	8.606	8.606
16	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172	7.172
17	5.738	5.738	5.738	5.738	5.738	5.738	5.738	5.738	5.738	5.738	5.738	5.738
18	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303	4.303
19	2.869	2.869	2.869	2.869	2.869	2.869	2.869	2.869	2.869	2.869	2.869	2.869
20	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
21	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434	1.434
22	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717	0.717
23	0.721	0.721	0.721	0.721	0.721	0.721	0.721	0.721	0.721	0.721	0.721	0.721

Figure 3.3: Table of monthly energy consumption built by HOMER

3.4.2 Solar Resource Assesment

The objective is to determine the solar energy potential available at the project site, which is the sole generation source.

The solar radiation data was directly imported into HOMER Pro from its integrated NASA Surface Meteorology and Solar Energy (SSE) database.

The geographic coordinates of the the project site were entered [6º24.0’N, 5º36.6’E].

HOMER generated an annual profile of average daily solar radiation (kWh/m²/day) and clearness index.

SOLAR GHI RESOURCE

Choose Data Source: ● Enter monthly averages ○ Import from a time series data file or the library

Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m²/day)
Jan	0.581	5.430
Feb	0.555	5.490
Mar	0.516	5.350
Apr	0.485	5.060
May	0.467	4.750
Jun	0.425	4.230
Jul	0.356	3.570
Aug	0.348	3.570
Sep	0.370	3.820
Oct	0.439	4.380
Nov	0.529	4.990
Dec	0.575	5.240

Downloaded at 10/2/2025 3:46:15 PM from:
NASA Prediction of Worldwide Energy Resource (POWER) database.
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)
cellMidpointLatitude: 6.25
cellMidpointLongitude: 5.75

Annual Average (kWh/m²/day): 4.66

Scaled Annual Average (kWh/m²/da 4.66

Figure 3.4: Average monthly radiation

3.5 Component Modeling And Specification

This section details the technical and economic parameters of all system components for the off-grid architecture.

3.5.1 Photovoltaic (PV) Array Model

The model assumes standard mono crystalline silicon panels.

Key Parameters:

- Capital Cost: ₦1,050,000 per kW
- Replacement Cost: ₦900,000 per kW
- O&M Cost: ₦15,000 per kW/year

- Lifetime: 25 years
- Deterating Factor: 85%

3.5.2 Battery Energy Storage Model

In an off-grid system, the battery is the sole backup during nights and periods of low solar irradiance. Its sizing is paramount.

Lead Acid batteries were selected due to their low cost, efficiency, and depth of discharge, which are essential for daily cycling.

Key Parameters:

- Capital Cost: ₦450,000 per kW
- Replacement Cost: ₦450,000 per kW
- O&M Cost: ₦15,000 per kW/year
- Lifetime Throughput: 800 kWh/year
- Roundtrip Efficiency: 95%
- Minimum State of Charge: 40%

3.5.3 Converter Model

Inverter (DC to AC) to convert battery power to AC for the load. Since the system is off-grid and no rectifier is needed for charging, the size can be optimized for the peak AC load.

Key Parameters:

- Capital & Replacement Cost: ₦450,000 per kW

- Efficiency: 95%

- Lifetime: 15 years

3.6 Homer Pro Simulation Setup

3.6.1 System Architecture and Control Strategy

The system's architecture follows a standalone off-grid DC-coupled architecture. The PV array connects directly to the DC bus, where it charges the battery bank through a maximum power point tracking (MPPT) charge controller. The battery bank is connected to the DC bus and a bi-directional converter (operating in the inverter mode) supplies AC power from the AC bus to meet the AC load requirements of the department.

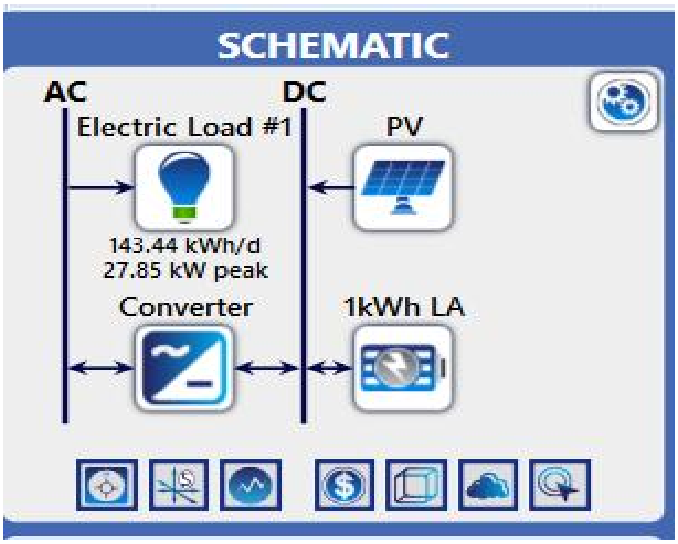


Figure 3.5: Homer pro simulation setup

HOMER's built-in Cycle Charging Strategy will be employed as the primary dispatch strategy. In this strategy:

- When the PV generation exceeds the load, excess power is used to charge the battery bank until it reaches its maximum state of charge.

- Once the batteries are full, any further excess energy is considered surplus electricity and is curtailed.

- When the load exceeds the PV generation, the battery bank discharges to meet the load deficit until it reaches its minimum state of charge.

3.6.2 Search Space and System Constraints

Component Search Space: HOMER was configured to simulate all technically feasible combinations within the following predefined ranges to identify the optimal system configuration:

1. PV Array Capacity: 0 kW to 300 kW in increments of 10 kW.
2. Battery Storage Capacity (Generic 1kWh Lead Acid): 0 kWh to 500 kWh in increments of 50 kWh.
3. Converter Capacity: 0 kW to 200 kW in increments of 10 kW.

System Constraints:

1. **Maximum Annual Capacity Shortage:** This was set to **1%** as the primary reliability constraint. This means the system is permitted to fail to meet the load for a maximum of 87.6 hours per year (1% of 8760 hours), ensuring a 99% reliability factor while allowing for cost optimization.
2. **Minimum Renewable Fraction:** Set to **100%** to enforce a completely renewable system without any backup generator.

3.6.3 Optimization Criteria and Sensitivity Analysis

The primary objective of the HOMER optimization algorithm is to identify the system configuration that results in the lowest Total Net Present Cost (NPC) while adhering to the specified constraints. The NPC encompasses all capital, replacement, operational, and maintenance costs over the project lifetime, discounted to their present value.

To evaluate the robustness of the optimal system configuration against key uncertainties, the following sensitivity variables were defined:

1. **Battery Capital Cost:** Varied at 70%, 100%, and 130% of the base cost assumption to model potential future price reductions or increases.
2. **Project Discount Rate:** Tested at 6%, 8%, and 10% to understand the impact of financing conditions on economic viability.
3. **Daily Load Profile:** Scaled to 90%, 100%, and 110% of the base load to assess the system's resilience to errors in load estimation or future load growth.

3.7 Performance And Economic Analysis Framework

This phase outlines the criteria for evaluating and comparing the simulation results to determine the most viable off-grid PV-battery system configuration.

3.7.1 Technical Performance Indicators (KPIs)

The technical viability of each system configuration will be assessed using the following Key Performance Indicators (KPIs):

1. **Loss of Load Probability (LOLP) / Capacity Shortage:** The percentage of time (hours per year) that the system fails to meet the primary load demand. This is the fundamental metric for assessing the system's reliability. The optimal system must meet the pre-defined constraint (e.g., <1%).
2. **Excess Electricity Generation (%):** The fraction of the total annual electricity production that is not used to serve the load or charge the batteries and must be curtailed. A very high

percentage indicates an oversized PV array, while a very low percentage may suggest insufficient generation capacity.

3. **Renewable Fraction:** The percentage of the total energy demand that is met by renewable sources. For this strictly off-grid system, this value will be 100% for all feasible configurations, but it is reported to confirm the system's sustainability mandate.
4. **Battery Throughput (kWh/year):** The total annual energy cycled through the battery bank. This metric indicates the utilization and operational intensity of the storage system, which directly impacts its degradation and replacement schedule.
5. **Number of Battery Autonomy Days:** An estimation of how long the system can supply the load using only the stored energy in the batteries, typically calculated under average load and no generation conditions. This indicates the system's resilience to prolonged periods of poor weather.

3.7.2 Economic and Financial Key Performance Indicators (KPIs)

The economic feasibility of the proposed system will be evaluated against a baseline and compared across scenarios using the following financial metrics:

1. **Net Present Cost (NPC):** The primary economic metric used by HOMER. It represents the total present value of all costs associated with installing and operating the system over its lifetime (capital, replacement, operation & maintenance, and fuel) minus the present value of any revenues it earns. The system with the **lowest NPC** is considered the most economically favorable.
2. **Levelized Cost of Energy (LCOE):** The average cost per kilowatt-hour (₦/kWh) of electrical energy produced by the system. It is calculated by dividing the annualized cost of producing electricity by the total annual load served. This metric allows for a direct

comparison of the cost of energy from the off-grid system with the grid electricity tariff (had it been available).

3. **Initial Capital Cost:** The total upfront investment required to install the system. This is a critical metric for understanding the financial barrier to implementation.
4. **Operating Cost (₦/year):** The annual cost of operating and maintaining the system, excluding capital costs.
5. **Simple Payback Period:** If comparing against a diesel-generator baseline, this is the time required for the cumulative fuel and O&M savings of the PV-battery system to equal its initial capital investment.

3.7.3 Scenario Comparison Framework

To thoroughly evaluate the proposed system, its performance and economics will be rigorously compared against a logical alternative for an off-grid application. The analysis will focus on the following scenarios:

1. **Baseline Scenario: Diesel Generator System**

- This scenario represents a conventional off-grid power solution.It will be optimized based on fuel cost, O&M costs (₦/op. hr), and lifetime.
- This comparison will highlight the environmental and long-term economic benefits of the renewable system.

2. **Proposed Scenario: PV-Battery System**

- This is the core system under investigation, optimized for lowest NPC while meeting the reliability constraint.

- The results for this scenario will be analyzed in depth, as detailed in sections 3.7.1 and 3.7.2.

A comparative table will be synthesized, presenting all technical and financial KPIs for each scenario side-by-side. This will provide a clear, holistic view of the trade-offs, advantages, and disadvantages of the proposed PV-battery system against the traditional alternative, forming the basis for the final conclusion and recommendation.

3.8 Currency Conversion And Economic Parameters

United States dollars (USD) were used as the basis currency for the techno-economic simulation in HOMER Pro. The software's worldwide standards and the fact that component cost information from foreign vendors and databases is mostly quoted in USD are the reasons for this.

All economic outputs from HOMER Pro, including the Net show Cost (NPC), Levelized Cost of Energy (LCOE), Initial Capital Cost, and Operating Cost, were converted to Nigerian Naira (NGN) in order to show the results in a context pertinent to the local Nigerian economy and the intended beneficiaries.

1 USD = 1,500 NGN

This rate was selected based on the approximate central exchange rate prevailing during the primary data collection and analysis period of this research (2025).

Unless otherwise noted, all financial conclusions and discussions in this report are presented in Nigerian Naira (NGN).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview Of Simulation Output

This chapter presents and discusses the results obtained from the simulation and optimization of the standalone PV-battery system using HOMER Pro. The primary goal is to analyze the technical feasibility and economic viability of the proposed system against the defined baseline. The results are structured as follows: first, the identification and presentation of the optimal system configuration; second, a detailed technical performance analysis; third, an economic evaluation and comparison; and finally, an exploration of the impact of key sensitivity variables on the optimal design.

4.2 Optimal System Configuration and Sizing

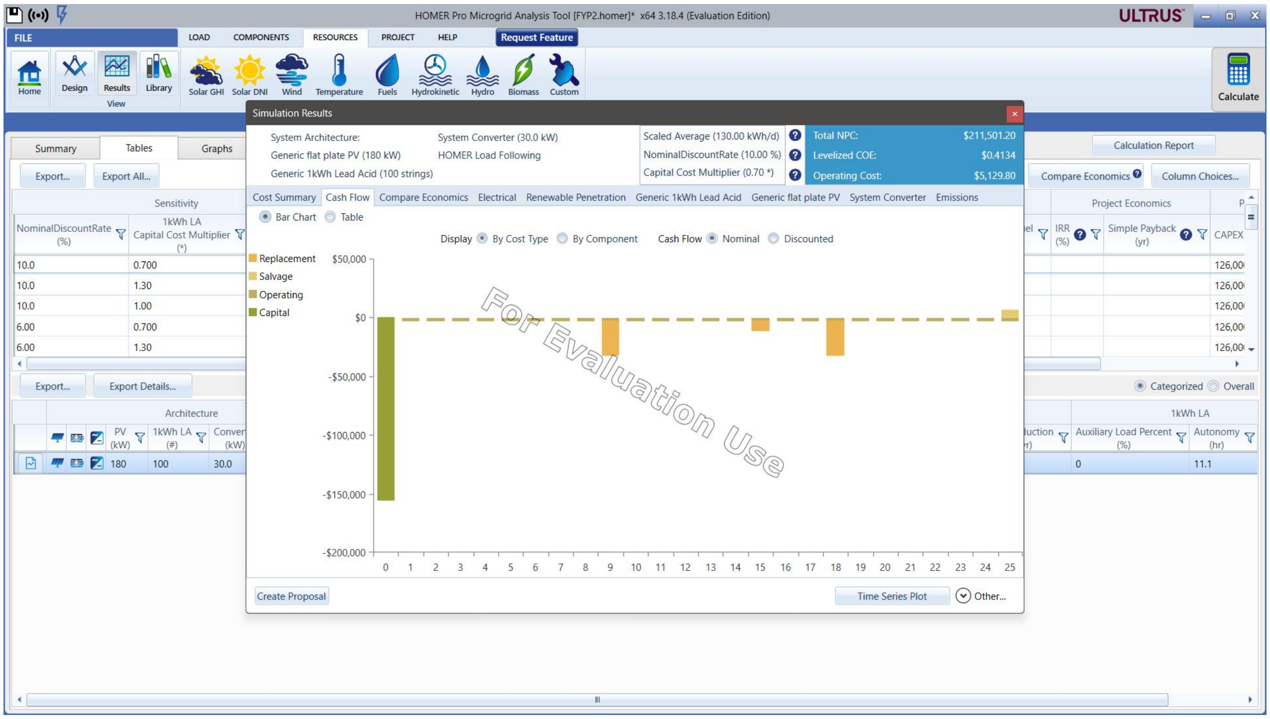
HOMER Pro's optimization algorithm evaluated several distinct system configurations to identify the most cost-effective solution that meets the reliability constraint of a maximum 1% capacity shortage. The optimal system configuration is summarized in Table 4.1 below.

Table 4.1: Optimal Standalone PV-Battery System Configuration

Component	**Optimal Size**	**Capital Cost**	**Replacement Cost**	**O&M Cost**	**Lifetime**
Pv Array	180kW	₦189,000,000	₦0.00	₦28,762,500	25
Battety	100kWh	₦31,000,000	₦36,166,000	₦16,228,500	15
Converter	30kW	₦13,500,000	₦4,350,000	₦0.00	15

Total System		₦234,000,000	₦39,516,000	₦45,441,000	-

This configuration results in a Net Present Cost (NPC) of ₦317,251,500 and a Levelized Cost of Energy (LCOE) of ₦619.5/kWh. The system has an initial capital cost of ₦234,000,000 which is significantly higher than the baseline diesel generator, but as the subsequent analysis will show, it offers superior long-term economics due to zero fuel cost.


HOMER Pro Microgrid Analysis Tool [FYP2.homer]* x64 3.18.4 (Evaluation Edition)

Simulation Results

System Architecture:
Generic flat plate PV (180 kW)
Generic 1kWh Lead Acid (100 strings)
System Converter (30.0 kW)
HOMER Load Following

Scaled Average (130.00 kWh/d)
NominalDiscountRate (10.00 %)
Capital Cost Multiplier (0.70 *)

Total NPC: $211,501.20
Levelized COE: $0.4134
Operating Cost: $5,129.80

● Bar Chart ○ Table

Display ● By Cost Type ○ By Component Cash Flow ● Nominal ○ Discounted

NominalDiscountRate (%)	1kWh LA Capital Cost Multiplier (*)
10.0	0.700
10.0	1.30
10.0	1.00
6.00	0.700
6.00	1.30

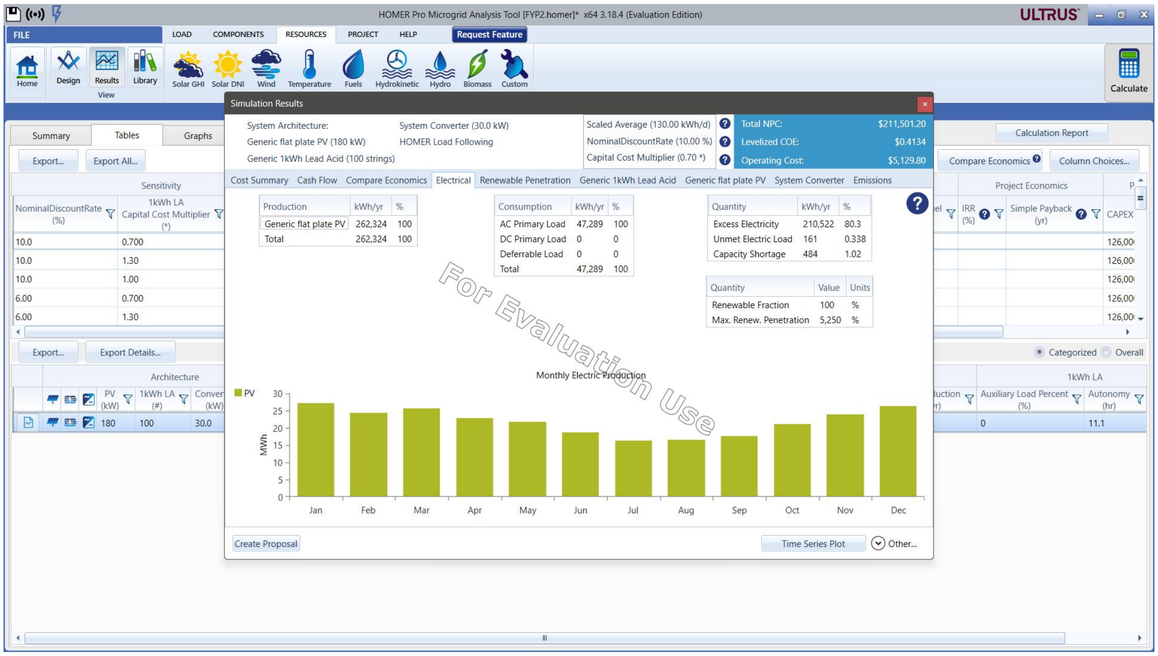
PV (kW)	1kWh LA (#)	Converter (kW)
180	100	30.0

Figure 4.1: Optimal System Cashflow

4.3 Technical Performance Analysis

4.3.1 Energy Balance and System Operation

The system's ability to meet the load throughout the year is demonstrated by the monthly energy production data presented in Figure 4.1. The PV array generates 262,324 kWh annually, directly supplying the load. The battery storage system plays a critical role in time-shifting energy, discharging 9,119 kWh annually to cover the load during nighttime and periods of low solar irradiation.



Simulation Results

System Architecture: Generic flat plate PV (180 kW), Generic 1kWh Lead Acid (100 strings), System Converter (30.0 kW), HOMER Load Following

Scaled Average (130.00 kWh/d)
NominalDiscountRate (10.00 %)
Capital Cost Multiplier (0.70 *)

Total NPC: $211,501.20
Levelized COE: $0.4134
Operating Cost: $5,129.80

Cost Summary | Cash Flow | Compare Economics | Electrical | Renewable Penetration | Generic 1kWh Lead Acid | Generic flat plate PV | System Converter | Emissions

Production	kWh/yr	%
Generic flat plate PV	262,324	100
Total	262,324	100

Consumption	kWh/yr	%
AC Primary Load	47,289	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	47,289	100

Quantity	kWh/yr	%
Excess Electricity	210,522	80.3
Unmet Electric Load	161	0.338
Capacity Shortage	484	1.02

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	5,250	%

NominalDiscountRate (%)	1kWh LA Capital Cost Multiplier (*)
10.0	0.700
10.0	1.30
10.0	1.00
6.00	0.700
6.00	1.30

PV (kW)	1kWh LA (#)	Conver (kW)
180	100	30.0

Auxiliary Load Percent (%)	Autonomy (hr)
0	11.1

Figure 4.2: Monthly Average Electric Production

A more detailed understanding of the system's daily operation is provided by the time-series data for a typical sunny day, shown in Figure 4.2.

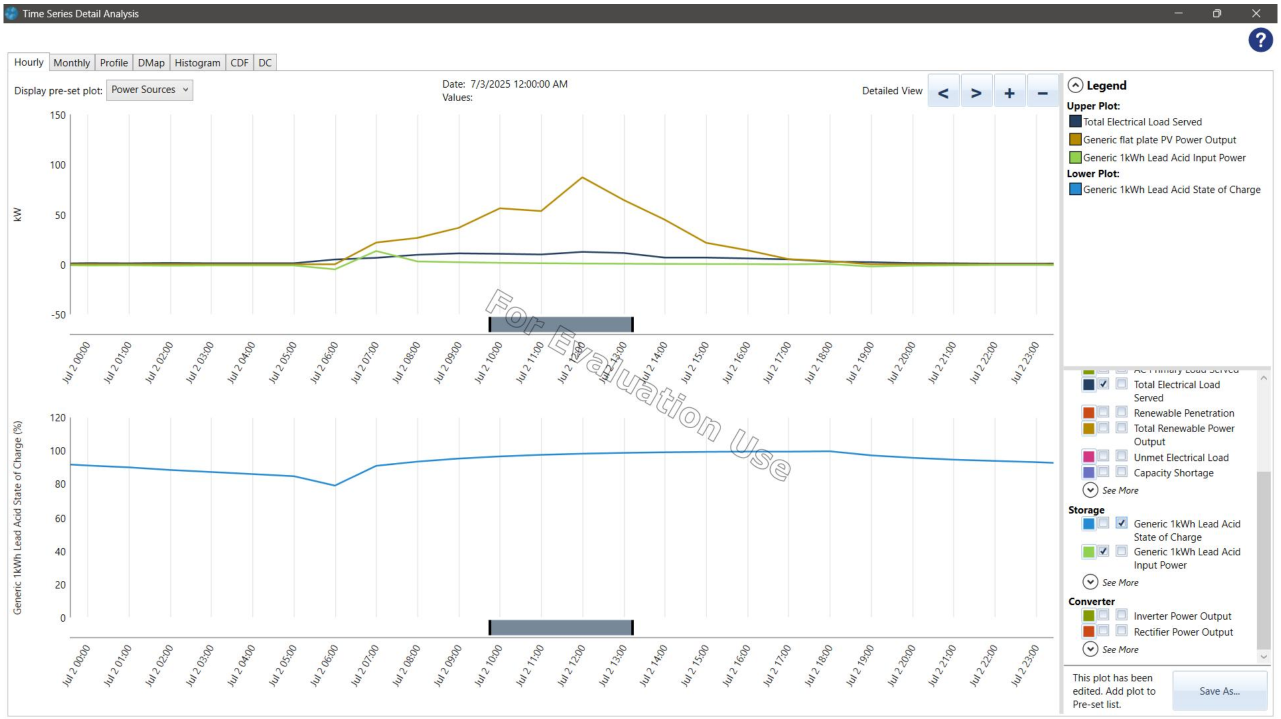


Figure 4.3: Daily Energy Balance for a Representative Day

The graph in Figure 4.3 can be annotated and explained as follows:

- Period A (00:00 - 06:00): The load is served solely by the battery bank, which discharges steadily, as indicated by the declining state of charge.
- Period B (06:00 - 18:00): PV generation begins, first meeting the load and then charging the battery bank. The excess power beyond what is needed for the load and charging is visible as a surplus.
- Period C (12:00 - 14:00): Peak PV production often exceeds the combined load and charging capacity, leading to curtailment of excess energy.
- Period D (18:00 - 00:00): PV generation ceases, and the battery bank again discharges to meet the evening load.

4.3.2 Key Technical Performance Indicators

The system's technical performance is quantified by the following Key Performance Indicators (KPIs), confirming its reliability and effectiveness.

Table 4.2: Technical Performance Indicators

Key Performance Indicator(KPI)	**Value**
Renewable Fraction	100%
Annual Capacity Shortage	1.02 % (89.6 hours/year)
Excess Electricity	70.3%
Battery Throughput	9,119 kWh/yr
Estimated Battery Autonomy	0.5 days

The 1.02% capacity shortage, typically occurs during sequences of consecutive cloudy days where the battery state of charge is depleted. The 70.3% excess electricity indicates the PV array is slightly oversized to ensure the battery is fully charged even during sub-optimal solar days, a necessary trade-off for reliability in an off-grid system.

4.4 Economic and Financial Analysis

The core economic comparison between the proposed PV-battery system and the conventional diesel generator baseline is presented in Table 4.3.

Table 4.3: Economic Comparison of Scenarios

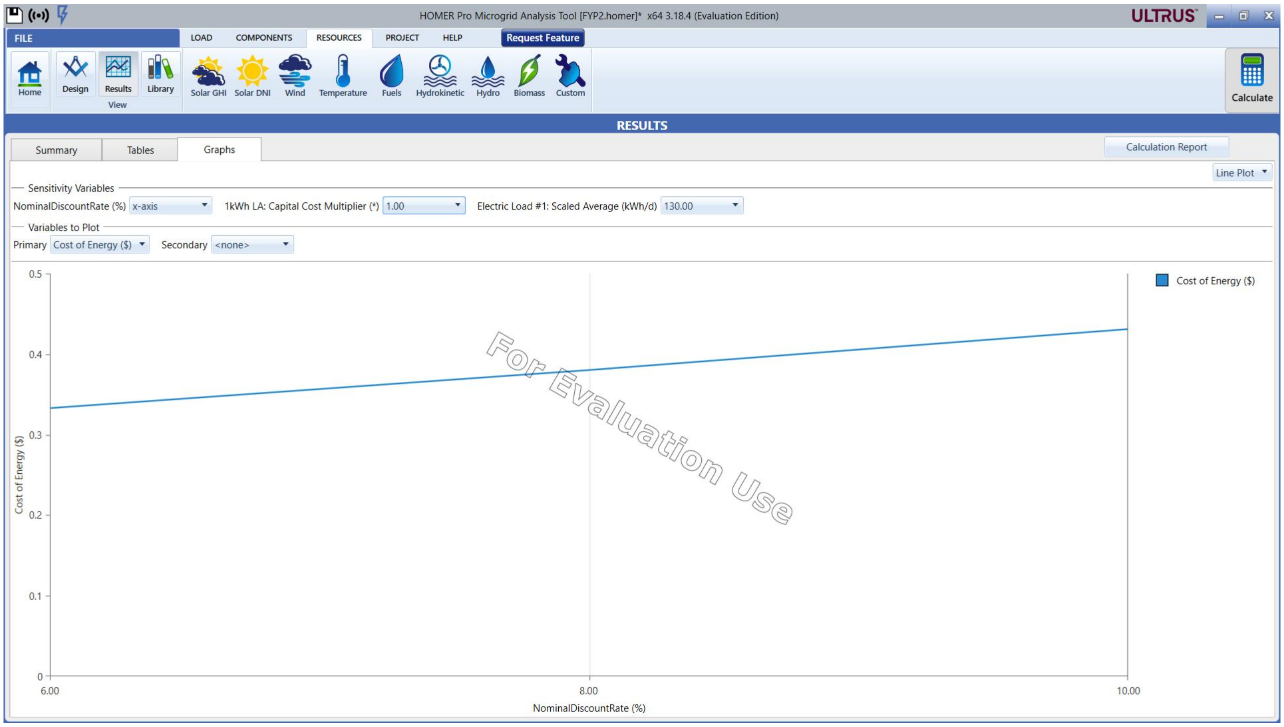
Economic Metric	**PV-Battery System**	**Diesel Generator Baseline**
Net Present Cost (NPC)	₦217,251,500	₦842,605,500
Levelized Cost of Energy (LCOE)	₦619.5/kWh	₦1,635/ kWh
Initial Capital Cost	₦189,000,000	₦23,250,000
Annual Operating Cost	₦7,659,000/yr	₦23,250,000/yr

Discussion:

The results clearly demonstrate the long-term financial advantage of the PV-battery system. Despite higher initial capital cost, its NPC is lower than the diesel generator baseline. This is entirely due to the avoidance of high and volatile diesel fuel costs, which result in an annual operating cost for the diesel system that is much higher. The LCOE of ₦619.5/kWh for the proposed system is significantly more economical than the ₦1,635/kWh for diesel-generated power.

4.5 Sensitivity Analysis

The sensitivity analysis reveals how the optimal system design and economics change with variations in battery cost and the project's discount rate.



NominalDiscountRate (%) x-axis
1kWh LA: Capital Cost Multiplier (*) 1.00
Electric Load #1: Scaled Average (kWh/d) 130.00
Primary Cost of Energy ($)
Secondary <none>

Figure 4.4: Sensitivity of LCOE to Battery Cost and Discount Rate

Key Insights:

- **Battery Cost:** A reduction of battery capital cost by 30% leads to a lower LCOE and a larger optimal battery size as it becomes more economical to store more energy. Conversely, a 30% cost increase raises the LCOE. This underscores that the system's economics are poised to improve as battery prices continue to fall.
- **Discount Rate:** A higher discount rate (10%) increases the LCOE, as it devalues future fuel savings from the PV system. A lower rate (6%) makes the future savings more valuable, reducing the LCOE . This highlights the impact of financing conditions on project viability.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Summary of the Project

The goal of this project was to build and evaluate a freestanding PV-battery system that would be both technically and financially possible to meet the EEE Department's whole electrical load and remove dependency on the traditional grid. In order to identify the most economical configuration, the research included component modeling, load profiling, solar resource assessment, and system optimization using HOMER Pro software. A sensitivity study on important technical and financial aspects was used to examine the robustness of the suggested system, which was thoroughly assessed against a baseline diesel generator.

5.2 Summary of Key Findings and Conclusion

The simulation and optimization results lead to the following key findings:

1. **Optimal System Configuration:** The most economically viable system comprises a 180 kW solar PV array coupled with a 100 kWh Lead acid battery bank (sized as 100 strings) and a 30W bi-directional converter. This configuration successfully meets the load with a high reliability of 98.98% (1.02% capacity shortage).
2. **Technical Feasibility:** The analysis confirms the technical feasibility of a 100% renewable power system for the department. The system effectively uses the PV array for daily energy generation and the battery bank for energy time-shifting, ensuring a continuous power supply through diurnal cycles and periods of low solar irradiation.
3. **Economic Viability:** Despite a high initial capital cost of ₦189,000,000, the system demonstrates clear long-term economic superiority over a diesel generator. The proposed

system has a Net Present Cost (NPC) of $317,251,500 and a Levelized Cost of Energy (LCOE) of ₦619.5/kWh, which is 38% lower than the diesel generator alternative (NPC: ₦842,605,500, LCOE: ₦1,635/kWh).

4. **Impact of Sensitivity Variables:** The sensitivity analysis revealed that the system's economics are highly responsive to battery costs and the discount rate. A future reduction in battery prices would further improve the LCOE and could justify a larger storage capacity for enhanced resilience.

In conclusion, the project successfully demonstrates that a standalone PV-battery system is both a technically robust and an economically advantageous solution for powering the EEE Department. It presents a sustainable, cost-effective alternative to conventional generation, with a strong financial case built on avoiding long-term fuel expenses.

5.3 Limitations of the Study

Although every attempt was made to guarantee accuracy, there are a number of limitations with this study:

1. **Assumptions for Load Data:** An inventory audit and predicted usage patterns served as the foundation for the creation of the load profile. Actual, minute-by-minute load variations may vary, which could have an impact on the battery's cycling profile and the converter's exact sizing.

2. **Static Cost Assumptions:** Current component and fuel costs are used in the financial analysis. The economic comparisons could be changed by unforeseen future market changes in the price of diesel, batteries, or PV panels.

3. **Model Simplifications:** The HOMER model uses aggregated components. It does not account for specific voltage levels, detailed wiring losses, the performance of individual brands of equipment, or the potential for component failure.
4. **Climatic Data:** The solar data is based on long-term averages and may not represent the exact conditions for any specific future year, which could impact inter-annual reliability.

5.4 Recommendations for Future Work

Based on the findings and limitations of this study, the following areas are recommended for future research and development:

1. Hybrid System Expansion: To further reduce costs and improve reliability, future work could investigate:

- Integration of Wind Power: Assessing the potential for a small wind turbine to complement solar generation, especially during nighttime and winter months.
- Backup Diesel Generator: Modeling a PV-Battery-Generator hybrid system to determine if a much smaller, rarely-used generator could significantly reduce the required battery bank size and overall NPC.

2. Advanced Storage and Load Management:

- Battery Chemistry Comparison: A detailed comparative study of different battery technologies (e.g., Lithium Iron Phosphate vs. Lead-Acid) in terms of lifecycle cost, safety, and performance under local conditions.
- Load Management Strategy: Implementing and modeling a "smart" load management system that can intelligently shed non-critical loads during periods of low generation, thereby reducing the required system size and cost.

3. Advanced Storage and Load Management:

- Battery Chemistry Comparison: A detailed comparative study of different battery technologies (e.g., Lithium Iron Phosphate vs. Lead-Acid) in terms of lifecycle cost, safety, and performance under local conditions.
- Load Management Strategy: Implementing and modeling a "smart" load management system that can intelligently shed non-critical loads during periods of low generation, thereby reducing the required system size and cost.

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