RELIABILITY ASSESSMENT OF AN ISLANDED HYBRID PV - WIND-BATTERY SYSTEM FOR A RESIDENTIAL BUILDING IN BENIN CITY, EDO-STATE, NIGERIA.

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CERTIFICATION

The undersigned hereby certify that the undergraduate research project titled "Reliability Assessment of an Islanded hybrid PV -wind batteries systems for a residential building in Benin city Edo state Nigeria"was successfully conceptualized, designed and executed by the student team listed Onofuevure Jedidiah Uyota, Okorie Divine Tochukwu, Mike Christian and Igbinomwanhia Lucky,

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DEDICATION

This project is dedicated to God Almighty for His grace, provision, and blessing of good health throughout the duration of the work and also this project is also dedicated to our loving parents.

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We extend our deepest gratitude to Prof K.O.Ogbeide for his steadfast support and encouragement throughout the project. His invaluable insights, recommendations and guidance has been indispensable and we attribute our success confidently to his contributions.

We would like to express our heartfelt appreciation to our parents, whose unwavering belief in our abilities as individuals has inspired us to unite as a team, collaborate and achieve remarkable heights, their guidance and financial support have served as a constant source of encouragement and we are truly grateful for their unwavering backing.

Additionally we would love to express our gratitude to our relatives, friend, course-mates and lecturers whose various forms of support has helped and encouraged us to this moment we say a very big thank you.

ABSTRACT

The persistent unreliability of the national power grid in Nigeria has significantly hindered economic growth and forced residential consumers to rely on expensive, noisy, and polluting diesel generators to meet their daily electricity needs. This study investigates the technical and economic feasibility of an islanded hybrid photovoltaic (PV)–wind–battery energy system designed to reliably power a residential building in Benin City, Edo State. Using HOMER Pro simulation software, the research modeled and optimized the system for a 3-bedroom apartment with a daily load demand of 21.73 kWh, utilizing local meteorological data. The optimal system configuration was determined to include a 5 kW solar PV array, three 1 kW wind turbines, a 34.8 kWh battery bank, and a 3.5 kW converter. This configuration achieved a 100% renewable fraction and high reliability, with a Loss of Power Supply Probability (LPSP) of 0.78% and a Loss of Load Expectation (LOLE) of approximately 22 hours per year. Economic analysis revealed a Net Present Cost (NPC) of ₦132,850,500 and a Levelized Cost of Energy (LCOE) of ₦1,305/kWh, placing the system within the competitive range of diesel-based alternatives.

Furthermore, a comprehensive sensitivity analysis confirmed that the system remained economically viable across all tested scenarios, affirming the suitability of hybrid renewable systems for off-grid residential applications in Nigeria

LIST OF FIGURES

LISTOFTABLES

TABLE OF CONTENTS

CHAPTER ONE

INTRODUCTION

1.1 Background

Energy resources are fundamentally categorized into two distinct classes: renewable and non-renewable. Renewable energy is derived from sources that naturally replenish over a human timescale, such as solar irradiance, wind dynamics, biomass, and hydroelectric potential. Conversely, non-renewable resources, including fossil fuels (coal, crude oil, natural gas) and nuclear elements like uranium, are finite and deplete with extraction.

In the context of sustainable power generation, solar and wind energy systems have emerged as critical alternatives. Solar technologies utilize photovoltaic (PV) modules to convert sunlight directly into electricity, while wind energy systems harness the kinetic energy of air currents through turbine rotors to drive electric generators. To address the intermittency inherent in these natural resources, they are frequently integrated into Hybrid Energy Systems (HES). These systems combine multiple generation sources—often augmenting renewables with battery energy storage or backup diesel generators—to ensure a reliable, efficient, and continuous power supply.

Such hybrid configurations can operate in two primary modes: grid-connected or islanded. An islanded (off-grid) system functions independently of the national utility grid, generating and managing its own power locally. This configuration is particularly vital for ensuring energy autonomy, reducing carbon footprints, and providing resilience against the frequent grid collapses experienced in developing regions.

1.2 Statement of Problem

The electricity supply sector in Nigeria is characterized by a significant deficit between generation capacity and peak demand, exacerbated by aging infrastructure and insufficient maintenance of power stations. This persistent unreliability forces residential consumers to resort to load shedding or self-generation. Consequently, households predominantly rely on fossil-fuel generators, which are not only expensive to operate due to volatile fuel prices but also contribute significantly to noise pollution and greenhouse gas emissions. There is, therefore, an urgent need to evaluate the technical and economic viability of alternative power solutions, specifically islanded hybrid renewable energy systems, to provide a sustainable and reliable power supply for residential users.

1.3 Aim

The primary aim of this research is to conduct a comprehensive reliability assessment and techno-economic analysis of an islanded hybrid PV–wind–battery system designed to power a residential building in Benin City, Edo State.

1.4 Objective

To achieve this aim, the study focuses on the following specific objectives:

1 To design a hybrid energy system architecture optimized for the specific load profile of a residential unit in Benin City, utilizing local solar and wind resource data.

2 To simulate and optimize the system configuration using Hybrid Optimization of Multiple Energy Resources (HOMER) Pro software.

3 To validate the system's reliability using quantitative indices, specifically the Loss of Power Supply Probability (LPSP) and Loss of Load Expectation (LOLE).

4 To evaluate the economic viability of the proposed system by analyzing the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) in comparison to conventional diesel generation.

1.5 Methodology

The following are steps we are taking in order to perform the research/study.

1 Site selection: Th**e** target area is a 3-bedroom residential building at the Senior Staff Quarters (SSQ) in the University of Benin, Benin City, Edo State.

2 Load Assessment: The load profile of the house is surveyed. Documenting the appliances, their usage and their conditions.

3 Data collection: detailed analysis of geographical and economic conditions affecting the solar installation/wind turbines. More Data collection on prices of the solar, wind and battery energy system prices plus other operational costs.

4 System Components and Design: The hybrid components will include solar PV, wind turbines, and a battery bidirectional inverter. The software used for the simulations and design of the system is called Hybrid Optimisation for Multiple Energy Resources (HOMER). It has two key products: the HOMER Pro for islanded systems and the HOMER Grid for grid-connected distributed energy systems. We will be making use of the HOMER Pro.

5. Reliability and economic analysis: Reliability of the system is analysed using the Capacity Outage Probability Table (COPT), Loss of Load Possibility (LOLP), Loss of Load Expectation (LOLE) and Expected Load Loss (ELL). These tables and calculations also help validate system robustness.

The economic analysis of the system will be made using the total Net Present Cost (NPC) and Levelised Cost of Electricity (LCOE).

6 Sensitivity Analysis: the analysis into the sensitivity of the hybrid system to various key parameters such as the environmental conditions and different economic conditions.

1.6 Scope

The scope of this work will be limited to a 3-bedroom apartment in Senior Staff Quarters at the University of Benin City. The data used will be peculiar to the building and will be gathered from the last three years. This study will examine the energy requirements of this residential building, and also study the future requirements, and possible scalability to support expansion will also be taken into consideration.

1.7 Significance

The significance of this research includes

1. This research will help to provide a clean environment by reducing the numbers of spills of diesel and oil in the grounds and also reduce emissions of CO_2.
2. This research will provide improvement to reliable energy and power supply being provided to residential buildings 24/7.
3. This research will provide renewable hybrid energy in more cost-efficient manner
4. This research can be implemented at any residential apartment in Benin City.
5. This research will greatly reduce the amount of noise in the environment due to the use of generators. will lead to advancement in hybrid energy system design, control and optimization. This will help drive innovations in energy storage technologies

CHAPTER TWO

LITERATURE REVIEW

2.1 REVIEW OF OTHER WORKS

Recent scholarship has prioritized the structural optimization of islanded hybrid microgrids, specifically regarding the evaluation of alternative dispatch strategies (Shezan et al., 2019). Key methodologies often employ simulation tools such as HOMER to assess the techno-economic feasibility of Hybrid Renewable Energy Systems (HRES). Beyond sizing, research has also focused on control techniques to mitigate voltage and frequency instability while minimizing net present costs. For instance, advanced strategies involving modified PI controllers and genetic algorithms (GA) have been utilized to regulate output voltage effectively.Optimal dispatch strategies are highlighted as important for minimizing power production and maximizing renewable energy resource use, including coordinated and optimal dispatch strategies and consideration of Vehicle-to-Grid (V2G) under Time-of-Use (TOU) tariffs.

Two-level decentralized optimization power dispatch control strategies for isolated micro grids without communication networks are presented to maintain frequency within a dedicated range and minimize operating costs, utilizing a first-level decentralized droop compensation control strategy for load sharing.

The paper cites reviews on size optimization methodologies for standalone solar and wind hybrid renewable energy systems and software tools for hybrid renewable energy systems.

Operational efficiency in DC microgrids has been addressed through novel hybrid control techniques, particularly for systems operating in islanded modes (Mortezapour et al., 2022). Rather than focusing solely on sizing, these studies emphasize the importance of combined primary and secondary control approaches. Such mechanisms facilitate effective power sharing between distributed energy resources (DERs) and ensure voltage regulation, often utilizing droop mechanisms based on local variable measurements to circumvent communication delays.

The safety and reliability of Distributed Generation (DG) systems rely heavily on robust Islanding Detection Methods (IDMs) (Kim et al., 2019). While distinct from general HRES sizing optimization, effective islanding detection is critical for the safe integration of distributed resources. Similarly, the role of flexible energy storage in stabilizing supply and demand within insular grids has been highlighted as a key factor for maintaining power quality during large-scale wind integration (Rodrigues et al., 2020).

(Ranjan et al. (2021) provides a comprehensive review of different control strategies adopted in isolated and interconnected multi-area hybrid power systems. The focus is on maintaining smooth operation by restraining frequency and voltage deviation, eRanjan reliability and power quality. Optimisation is discussed in the context of controller tuning. The paper mentions that an accurate and adequate control strategy is inevitable for smooth operation.

Isolated hybrid power systems, combining energy storage systems with integrated variable renewable energy sources (RES), aim for reduced reliance on traditional units and can provide ancillary system services.

Energy storage controllers (ESCs) are essential for managing the intermittency of RES by injecting or absorbing active power to control frequency deviation.

Energy management and demand response are highlighted as important for controlling deviations in system parameters, with customer involvement playing a crucial role.

Various traditional controllers like Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) are used.

Advanced controllers like H∞, Two Degree of Freedom (2DOF) PI/PID, and fractional-order (FO) -based controllers are also employed.

Optimisation tools are crucial for tuning these controllers, with intelligent techniques such as Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), Fuzzy Logic Control, Yellow Saddle Goatfish Algorithm (YSGA), and Butterfly Optimisation Technique (BOA) being used.

The Mine Blast Algorithm (MBA) is presented as a technique used to optimize controller parameters in three-area hybrid power systems with different renewable sources and storage. The paper concludes that MBA-based 2DOF PID controllers can outperform other controlling strategies for HPS.

Islam et al. (2021) review islanding detection and energy management systems (EMS) for micro grids, including isolated ones. The focus is on operational optimization and reliability:

The paper discusses different EMS architectures: centralized, decentralized, and hybrid, each with its own optimization approach for managing energy resources and exchanges. Centralized EMS aims for global optimal solutions for multi-objective energy management. Decentralized EMS involves local optimization by individual units. Hybrid EMS combines local optimization with central coordination.

Various metaheuristic techniques are reviewed for optimal EMS, including differential evolution, ant colony optimization, modified firefly technique, tabu search algorithm, artificial bee colony, cuckoo search optimization, and modified bat algorithm, each aiming to minimize different objectives like operating costs, GHG emissions, or functional costs. Many of these studies use centralized supervision control for MG energy management. The paper highlights the need for further research to combine goals like reducing running costs, power system losses, battery degradation cost, and environmental pollution while ensuring reliable MG operation and reducing computational difficulty.

This short excerpt (Worku et al., 2021) cites a review on islanding detection methods (IDMs) in DG systems and an article on a hybrid synchrophasor and GOOSE-based passive islanding scheme.

This paper (Padrón et al., 2019) focuses on modelling hybrid systems with renewable energy for autonomous desalination systems (ADS) on islands with high wind and solar radiation, specifically Lanzarote and Fuerteventura in the Canary Islands. The core optimization method used is the HOMER Hybrid Optimisation Model Tool. HOMER is used to create optimal designs by considering electric demand, equipment specifications, solar radiation, and wind speeds. The objective is to propose the "best renewable hybrid system" from a techno-economic point of view to guarantee power for ADS with a daily production of up to 50m. Several configurations of photovoltaic (PV) modules, wind turbines, and battery banks are simulated, with the possibility of including diesel generators. The optimization considers both technical and economic merits.

The dispatch strategy used in HOMER was "load-following". The paper presents the most economic HRES configuration resulting from the HOMER simulations for Lanzarote and Fuerteventura, including specific component sizes and costs.

(Lassalle et al., 2002) a comprehensive review of HRES optimization on 73 island cases. It analyses energy demand, system sizes, and optimization methodologies.

The paper identifies three stages of HRES optimization: renewable energy assessment, energy consumption assessment, and sizing and energy optimization.

The optimization objectives in the reviewed studies are categorized as economic (e.g., minimizing NPC, COE), environmental (e.g., maximizing RES penetration, minimizing emissions), technical (e.g., performance evaluation), and multi-objective. Economic objectives are the most common. Numerous energy optimization tools and frameworks are discussed, with HOMER software being the most used. Techno-economical models are also applied.

The most typical generation mix found is wind and solar energy with diesel backup.

Energy storage is considered in most studies to increase RES penetration, with electrochemical batteries being the most common for smaller systems and pumped battery. for larger ones. Hydrogen storage is also considered.

The most common hybrid energy mix is wind/solar/diesel with electrochemical battery. The paper recommends considering a multi-objective analysis approach that includes economic and environmental factors.

Emergent methods like demand-side management and green hydrogen generation are highlighted as important considerations for future HRES optimization on islands.

Phan et al. (2019) focuses on the control strategy of a hybrid renewable energy system based on a reinforcement learning approach for an isolated microgrid. It also discusses optimal sizing and maximum power point tracking (MPPT) control.

The paper uses HOMER software for the optimal sizing of a hybrid renewable hydrogen energy system for an island in the Philippines, aiming for the lowest net present cost (NPC) and cost of energy (COE) while meeting load demand.

The optimization criteria generally consider economic and power reliability factors.

The paper reviews various methodologies for unit sizing of HRES components, including artificial intelligence, multi-objective design, iterative techniques, and probabilistic approaches. AI and multi-objective design are noted as powerful tools.

The paper proposes a hybrid perturbation and observation (P&O) and Q-learning (h-POQL) MPPT method for a photovoltaic (PV) system, demonstrating improved performance compared to the P&O method. This is an optimization at the component level.

It reviews energy management systems (EMS) architectures (centralized, distributed, hybrid) and intelligent control strategies like fuzzy logic control (FLC), artificial neural network (ANN), adaptive neuro-fuzzy inference system (ANFIS), models. predictive controller (MPC), and evolutionary algorithms (PSO, GA) for optimal energy management. Reinforcement learning (RL) is highlighted as an emerging optimal control solution.

The use of multi-agent systems (MAS) with reinforcement learning for energy management is also discussed.

2.2.1 Energy Systems

Energy systems are a crucial part of our society as an engineer it is our job to understand, analyses and find new ways to improve it.

Energy systems refers to the design, development and operation of interconnected systems that generate, transmit, distribute and utilize energy. They include all the components like power plants, batteries, transmission lines, and engines that transform energy from one form to another to meet human or industrial needs.

These system encompass various form of different energy including fossil fuels, renewable sources and nuclear power. These systems are fundamental to meting societal energy demands while addressing technical, economic, and environmental challenges. Energy systems is a multi-disciplined system focused on designing solutions that balance technological with environment and economic needs.

The research done by Pfenninger et al. defines energy system as a system that broadly encompasses the entire chain from primary energy extraction to its final use in providing services and goods within a given society or economy. While often focusing on technical and environmental elements, the primary goal of modeling these systems is to generate insight, not just numbers. The author also talked about the energy system in the twenty-first century, where there has been a renewed focus on improving energy systems analysis due to significant challenges and opportunities. Challenges include ensuring energy supply security, affordability, and resilience, alongside environmental concerns like local pollution and, most critically, climate change and global sustainability. Opportunities arise from bringing new technologies to market and fostering competitive new industries.

2.2.2 Hybridization of Energy Systems

Energy is the cornerstone of modern life powering homes, industries, healthcare, education, and transportation.

Over the past few decades, energy demand worldwide has grown rapidly, fueled by industrialization, urbanization, and population growth. However, traditional energy systems, heavily dependent on fossil fuels, have led to environmental degradation, resource depletion, and vulnerability to supply disruptions. Simultaneously, the increasing penetration of renewable energy sources (RES) like solar and wind has highlighted their potential to reduce carbon emissions and promote sustainability.

Yet, renewable energy systems face challenges such as intermittency, seasonal variability, and often the mismatch between energy supply and demand. Standalone renewable systems often cannot meet the reliability requirements of modern energy users, especially in isolated or off-grid areas.

To address these limitations, research and practice have increasingly turned toward Hybrid Energy Systems (HES) systems that combine two or more energy sources, often with energy storage, controlled by intelligent management systems. Hybridization aims to optimize resource use, increase reliability, reduce fuel costs, and minimize environmental impacts.

Today, HES are seen as a key element of the global energy transition and sustainable development, aligning with goals such as the United Nations Sustainable Development Goal 7: “Affordable and Clean Energy.”

In this context, the hybridization of energy systems has emerged as a practical and promising solution to overcome the limitations of individual energy sources while enhancing their benefits.

Hybridization refers to the integration of two or more different energy generation or storage technologies in a single, coordinated system to provide a reliable, efficient, cost-effective, and sustainable supply of energy.

It aims to combine complementary characteristics of various sources for example:

Renewable sources (solar & wind) for clean energy, Fossil-fuel generators for reliability when renewables are unavailable, Batteries or other storage to buffer fluctuations and store excess power.

This integrated approach ensures continuous power availability while minimizing costs and environmental impacts.

Importance of Hybridization

Hybridization is driven by the following needs:

1 To ensure reliability and stability of power supply in spite of variable renewable resources.

2 To reduce fuel costs and emissions by maximizing renewable energy use.

3 To provide energy access in remote or off-grid areas, where extending the central grid is expensive or impossible.

4 To make better use of local resources sun in desert areas, wind on coastal regions, biomass in rural areas, etc.

Components of a Hybrid Energy System

A typical hybrid energy system includes:

1 Primary renewable energy sources: solar PV, wind turbine, micro-hydro, biomass.

2 Backup/conventional sources: diesel or gas generator, grid connection.

3 Energy storage: batteries, pumped hydro, hydrogen fuel cells.

4 Control & power electronics: to manage the flow of energy between the different sources, storage, and loads.

These components are configured to maximize renewable contribution and minimize the use of fossil fuels while ensuring uninterrupted power.

Benefits of Hybrid Energy Systems

1 Increased reliability: multiple sources reduce risk of failure or blackouts.

2 Improved efficiency: better resource utilization and load matching.

3 Cost savings: lower fuel consumption and reduced operation & maintenance costs over time.

4 Environmental protection: reduced greenhouse gas emissions and pollution.

5 Energy access: critical for off-grid or rural communities.

Hybridization of energy systems represents an essential strategy in the transition toward a more sustainable and resilient energy future. By intelligently combining renewable and conventional energy sources with storage technologies, hybrid systems can deliver reliable, clean, and affordable power even in challenging environments.

As technology advances and costs of renewables and storage continue to fall, hybrid systems are expected to play a crucial role in global efforts to reduce carbon emissions, increase energy security, and expand access to modern energy services.

Hybrid energy systems (HES) can operate in two main modes, depending on whether they interact with the main electricity grid or not. These two modes are called:

1.Islanded (or Standalone/off-grid) Hybrid Systems: An islanded hybrid energy system operates independently of the central electricity grid. It is designed to supply electricity to areas where grid access is not available, unreliable, or economically unfeasible typically rural, remote, or island communities.

Key Features

1. Self-sufficient: Generates all the power needed locally.
2. Combines renewable sources (e.g., solar, wind, hydro) with storage (batteries) and sometimes backup generators (diesel, biomass).
3. Requires careful load management and adequate storage to match demand and supply. Power quality and stability are managed entirely by the system’s own control and inverter technologies.

Advantages:

1. Provides electricity where no grid exists.
2. Reduces reliance on expensive and polluting diesel.
3. Improves quality of life and economic opportunities in remote areas.
4. Encourages use of local renewable resources.

Challenges:

1. High initial capital cost.
2. Requires robust design to handle variability of renewables.
3. Maintenance can be challenging in isolated locations.

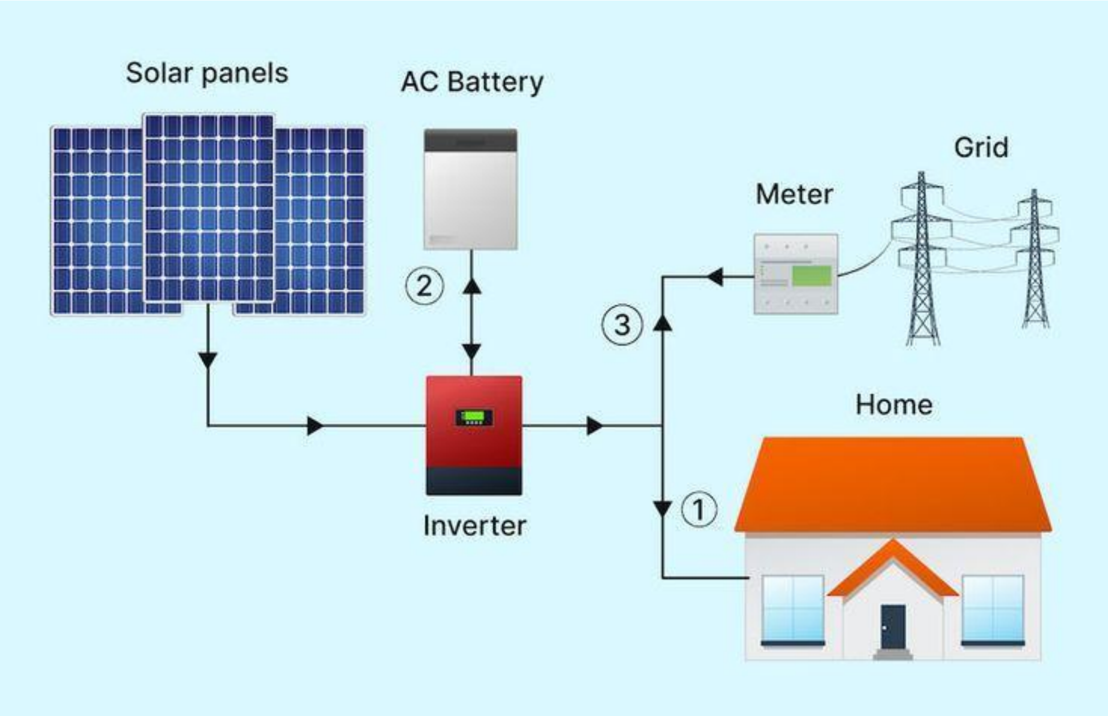

Fig 2. 1 Diagram of a Grid -Connected Energy Systems.

2 Grid-Connected Hybrid Energy Systems: A grid-connected hybrid energy system is connected to the central electricity grid but also has local generation and often storage. It operates in conjunction with the grid to optimize energy costs, reduce emissions, improve reliability, and sometimes even sell excess power back to the grid (net metering).

Key Features:

1. Supplements grid power with onsite renewable generation and storage.
2. Can export excess renewable energy to the grid or import power when local generation is insufficient.
3. often designed to reduce peak demand charges and improve energy security.
4. In some cases, can island temporarily during grid outages (if designed with that capability called “grid-forming” or “microgrid” mode).

Advantages:

1. Reduces electricity bills and demand charges.

2. Increases renewable energy use and lowers carbon footprint.
3. Provides backup power during grid outages (if equipped for islanding).
4. Easier to design since the grid provides backup capacity.
5. Most grid connect systems do not need extra batteries making them more cost-effective.

Challenges:

1. Requires compliance with grid codes and standards.
2. May involve interconnection fees and regulatory hurdles.
3. Grid outages can still affect the system those models without battery backup

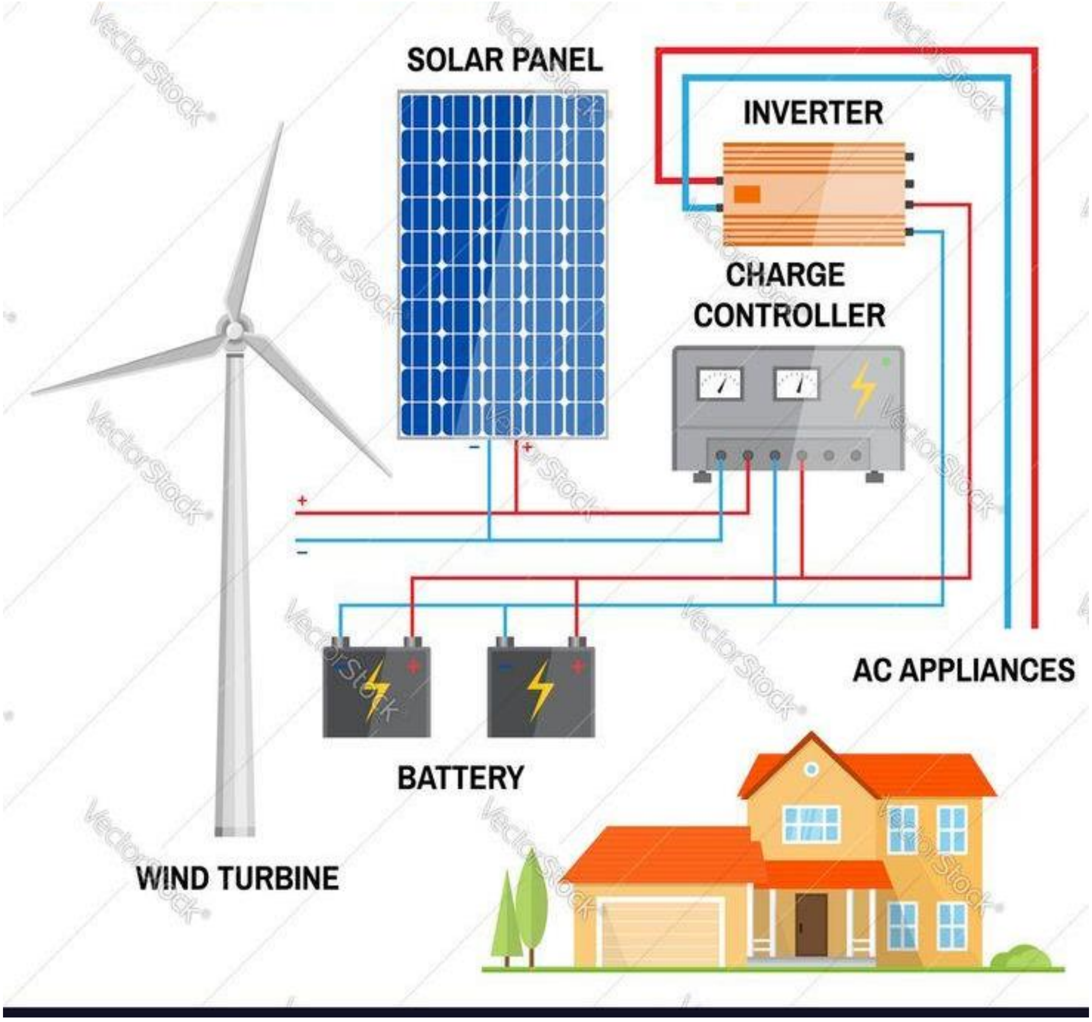

Fig 2.2 off- Grid Connected Hybrid System

Table 2.1 Operational Distinctions Between Standalone and Grid - tied configurations

Operational Asepct	**Off Grid HybridArchitecture**	**Grid- Intergrated Hybrid Architecture**
Grid Access	No	Yes
Purpose	Provide full power locally	Supplement & optimize grid use
Reliability and resilience	provides greater reliability during grid outages ensuring uninterrupted power supply	Grid provides backup making it vulnerable to grid outages
Excess Energy	Stored or curtailed	Can be exported to grid
Cost	Typically higher per due to higher initial investment	Lower due to grid support but entails electricity bills.
Applications	Remote areas, islands	Cities, industries, campuses
Storage Need	High (to cover all demand)	Optional or smaller (grid backup)

2.2.3 Islanded PV Wind Systems

The history of photovoltaic (PV) cells is marked by a series of observations, scientific breakthroughs, and technological advancements that transformed them from laboratory curiosities into a significant source of renewable energy.

Photovoltaic (PV) cells, commonly known as solar cells, are optoelectronic devices designed to convert sunlight directly into electricity through a phenomenon called the photovoltaic effect. This technology, which began with early scientific observations, has evolved into a significant component of the renewable energy industry.

The fundamental principle of a solar cell involves the photoelectric effect, first observed by Alexandre Edmond Becquerel in 1839 on silver and platinum electrodes exposed to sunlight. Later, in 1873, Willoughby Smith described this effect in selenium, leading to the development of the first solar cell using selenium in 1877 by Adams and Day, which achieved an efficiency of approximately 0.5%. Albert Einstein's photoelectric theory in 1905 further clarified the interaction of light quanta (photons) with electrons, for which he received the Nobel Prize in Physics in 1921.

A major leap for practical solar cells occurred in 1939 with Russell Ohl's discovery of n- and p-type regions in silicon and the photoelectric effect in p-n junctions, leading to the development of the first silicon solar cell in 1940 at Bell Labs. In 1954, Bell Labs chemist Calvin Fuller's silicon doping process enabled the creation of a p-n junction diode with an "astonishing efficiency of 6%".

Initially, these devices, due to their low efficiencies, were primarily used as sensors, such as in photography. However, their role quickly expanded. The first application of a solar cell as a power source for a telecommunication network was in Americus, Georgia, in 1955. Subsequently, PV cells gained prominence in space applications, powering satellites like NASA's Vanguard-I in 1958, which was equipped with six silicon solar cells that operated for eight years. The "war to discover space" significantly accelerated the advancement of photovoltaic technology.

Today, photovoltaic technology is a rapidly growing industry. While early solar cells used in applications like powering satellites were often expensive, driven by the oil crisis in the 1970s, new technologies and materials emerged to reduce manufacturing costs. This led to the categorization of solar cells into different "generations" based on their materials and production techniques. Photovoltaic technology now plays a crucial role in addressing climate change and meeting the increasing global demand for clean energy, aligning with global sustainable development goals.

Modern Generations and Future Outlook (2000s - Present): Currently, photovoltaic technologies are classified into generations based on their materials and manufacturing techniques.

The first generation remains dominated by wafer-based crystalline silicon, accounting for 95% of global PV power production as of 2020.

The second generation focuses on thin-film technologies, such as Copper Indium Gallium Selenide (CIGS) and Cadmium Telluride (CdTe), which aim for reduced material usage and lower production costs. These thin-film cells have reached efficiencies exceeding 20%.

The third generation moves beyond standard p-n junctions, employing novel materials and architectures like multi-junction (tandem) cells and Perovskite solar cells. Multi-junction devices, which stack different semiconductor layers to capture a broader spectrum of light, have achieved remarkably high efficiencies, with a record of 47.1% at 146 suns for a six-junction III-V solar cell.

Perovskite solar cells, first demonstrated in 2009, have rapidly advanced, particularly in tandem configurations with silicon, reaching efficiencies of 29.5%.

Ongoing research continues to address challenges such as cell degradation, performance under varying environmental conditions (temperature, irradiance, shading), and the development of cost-effective, large-scale production and recycling methods.

2.3 Components of Islanded Hybrid PV Wind Turbine Systems

2.3.1 Solar Panels

There are five major types of solar panels.

Polycrystalline solar panels As one of the foundational technologies in the photovoltaic market, polycrystalline panels are manufactured by melting raw silicon crystals together. While this process reduces manufacturing costs, it generally results in a lower efficiency threshold, typically ranging between 18% and 21%. Despite being less space-efficient than their monocrystalline counterparts, they remain a viable, durable option with an expected service life of over two decades . These blue panels are less efficient, less aesthetically pleasing, and less long-lasting than black mono crystalline panels. and though they're technically cheaper, this comes with a large drawback: they take up far more space, because they're significantly less efficient. Since 1984, the record efficiency of poly crystalline cells has increased from 15% to 23.3%.This is a decent level, but it's way behind mono crystalline, which hit 24% all the way back in 1994, according to the NREL. Since panels always lag behind cells in efficiency terms, the average poly crystalline panel today is even less impressive, at just 14.5%. This makes it 31% worse than the average mono crystalline panel, which is 21% efficient.

Fig 2.3 Polycrystalline solar panels

Monocrystalline solar panels Currently representing the industry standard for efficiency, monocrystalline panels are crafted from single-crystal silicon structures. This purity allows for electron flow with less resistance, resulting in efficiency rates typically exceeding 20%. Although they command a higher market price, their longevity and superior performance per square meter make them the preferred choice for projects where space is a constraint.

They also have a longer lifespan than any other type, on average, often outlasting their already lengthy performance warranties, which can stretch to 30 years. Mono-crystalline is currently the most cutting-edge solar material, too – bifacial solar panels are usually made with mono-crystalline, for instance. For all these reasons, 98% of global solar panel shipments in 2023 were made with mono-crystalline, up from 35% in 2015, according to the NREL. We have Polish scientist Jan Czochralski to thank for the creation of monocrystalline panels. In 1916, the 31-year-old absent mindedly dipped his pen into a crucible of molten tin instead of his inkwell, hurriedly took it out – and withdrew a narrow thread of metal at the same time. This was the eureka moment that enabled mono-crystalline silicon production. The Czochralski method, which was modelled on this accident, was crucial in Bell Labs researcher Russell Ohl’s development of the first mono-crystalline cell 25 years later, in 1941 – and that’s not all. This method is still used in the great majority of electronic goods around the world, from mobile phones and televisions to washing machines and fridges. On average, mono-crystalline solar panels are 31% more efficient than their closest rival, last around 18% longer, and are produced by all the leading solar manufacturers. The only major drawback when it comes to mono-crystalline panels is they’re usually more expensive than other widely available types but that's inevitable, since they're better.

Fig 2.4 Monocrystalline panels

Thin-film solar panels are flexible sheets that can wrap around objects, making them perfect for properties with a limited amount of unobstructed roof space, or mobile homes like recreation vehicles and houseboats. It has an efficiency of 17-19% and a life span of 10-20 yearsThey're thousands of times thinner than the average mono-crystalline panel, which gives them their malleable nature. Manufacturers create them by stacking several layers of solar material, like amorphous silicon, cadmium telluride, and copper indium gallium selenide. The creation of thin-film panels was kick-started by NASA in 1961, when the Photovoltaic Fundamentals Section at its Ohio research centre started developing the technology. They've since been used in space, with their flexibility and resilience proving an advantage over other types of panels when it comes to extraterrestrial uses. ARCO Solar released the first commercial thin-film solar panel, the G-4000, in 1986, and they've been on the market ever since. Thin-film efficiency levels are usually lower than those of monocrystalline panels, but they tend to still be pretty decent. Cadmium telluride (CdTe) panels, one of the most popular thin-film varieties, are around 17-19% efficient. The average for installed CdTe panels in the US in 2023 was 18.6%, according to the NREL, up massively from 11% in 2010. There are other thin-film types – the main one being copper indium selenide (CIS) and its related variation, copper indium gallium selenide (CIGS) – but CdTe is far and away the most popular. Thin-film efficiency is substantially lower than most other types of solar panels, though this is usually reflected in their relatively low prices.

Fig 2.4 Thin Film Solar Panels

Perovskite solar: Perovskite solar panels are at the forefront of solar innovation. They’re made with perovskite, a synthetic material based on the crystal structure of a mineral that’s (confusingly) also called perovskite. It has a 29-31% efficiency and a lifespan of 25-35 yearsA layer of this material is placed on a layer of silicon to create a ‘tandem’ panel – the advantage being that silicon can absorb light from the red part of the spectrum, and perovskite can absorb light from the blue end. Researchers have attempted to use its structure for electronic purposes since the 1950s, but it was only successfully incorporated into a solar cell in 2009, when University of Tokyo scientists made a perovskite cell with 3.8% efficiency. Since then, progress has been rapid. In June 2024, researchers at Chinese solar company LONGi created a perovskite-silicon cell with a record-breaking 34.6% efficiency. In June 2025, China's GCL broke the record for a whole panel, achieving a 29.51% efficiency rating – and just a few days later, rival firm Trina Solar went one better with a panel that's 30.6% efficient.

Fig 2.5 Peroviskite solar panel

Transparent Solar Panels: If they reach their final form, transparent solar panels could be efficient, fully see-through sheets of solar material, mostly made of glass, that replace windows, roofs, and phone screens all over the world.It has an efficiency of 1% and a life span of 25-35 years.However, semi-transparent panels – which are just 40-50% see-through – are around 20% efficient. In 2014, a team of researchers at Michigan State University (MSU) created a 100% transparent cell, but with an efficiency of around 1%.This cell was a transparent luminescent solar concentrator (TLSC) – a small, specially treated panel of glass surrounded by a narrow frame of solar material. There are other transparent cells made with monocrystalline or CdTe, but since the solar material involved is encased in glass, they'll never be more than about 50% transparent. In the years since, the industry hasn't managed to turn

MSU's breakthrough into a commercially viable TLSC panel with a higher efficiency rating than 1%. and unless their efficiency rises dramatically, 100% transparent panels won't be suitable for domestic properties. Semi-transparent panels are good for large buildings, including office blocks and skyscrapers, where they can make enormous energy savings across the hundreds of windows they replace.

Fig 2.6 Transparent solar panels

2.3.2 Wind Turbine

A wind turbine is a machine that converts the kinetic energy of wind into mechanical energy — and then into electricity using a generator.

Wind power has been harnessed for centuries. The first recorded use of wind energy solution dates back to 200 BC when simple windmills were used to pump water and grind grain. Today's wind turbines are highly efficient. On average, they convert about 40% of the kinetic energy in the wind into electricity, with some of the most advanced models achieving conversion rates of up to 50%.

Wind turbines are at the forefront of renewable energy generation when it comes to utilizing the power of the wind. These contemporary marvels come in a variety of sizes and forms, and each is made to effectively collect the kinetic energy of the wind.

There are two different types of wind turbines:

A. **Horizontal Axis Wind Turbines (HAWT):** Wind turbines like this usually have three blades, like airplane propellers. They're placed on a tall tower, with all their parts, including the blades, shaft, and generator, on top. The blades point towards the wind, and the shaft is flat. Most of the wind turbines we see are horizontal wind turbine. These are the most common types of wind turbines. They have a horizontal rotor shaft, with blades that resemble an airplane propeller. HAWTs are suitable for both small-scale residential installations and large utility-scale wind farms. A typical HAWT can generate electricity with capacities ranging from 1 kW to over 10 MW. In 2022, global HAWT installations contributed to over 97.3% of total wind power capacity.

Fig 2.7 Horizontal Axis Wind Turbines

B. **Vertical Axis Wind Turbines (VAWT):** The vertical-axis wind turbines have blades that are attached to the top and the bottom of a vertical rotor. The most common type of vertical-axis turbine—the Darrieus wind turbine, named after the French engineer Georges Darrieus, who patented the design in 1931—looks like a giant, two-bladed eggbeater. Some versions of the vertical-axis turbine are 100 feet tall and 50 feet wide. Very few vertical-axis wind turbines are in use today because they do not perform as well as horizontal-axis turbines. VAWTs have a vertical rotor shaft, with blades that rotate around it. They can capture wind from any direction and are often used in urban environments or where aesthetics is a concern. While less common than HAWTs, they have unique advantages of wind energy in certain applications. VAWTs are typically smaller, with capacities ranging from a few hundred watts to a few megawatts. These turbines account for about 5% of global wind power capacity in 2022.

Fig 2.8 Vertical Axis Wind Turbine

The Parts of A Wind Turbine

A wind turbine is made up of several crucial parts. The blades, which are normally three in number and serve to capture the wind’s energy, come first. A central shaft is attached to these blades. The shaft rotates in tandem with the blades because of the wind. A generator attached to the shaft transforms the mechanical energy from the rotating shaft into electrical power. The entire structure is put on top of a tall tower to sustain these parts and gather wind at a higher altitude. Together, these crucial components enable a wind turbine to capture wind energy and produce electricity.

Nacelle In Wind Turbines: A wind turbine’s nacelle is like a control center. This is a protective enclosure that houses critical components such as transmissions, generators, and other electrical and mechanical systems. The nacelle is typically located behind the turbine blades and mounted at the top of the tower. It plays an important role in maintaining and controlling the operation of the turbine, converting the mechanical energy of the rotating blades into electricity, and ensuring efficient and safe operation of the turbine.

Inside the nacelle, the following components can be found:

1. Generator: It is the generator’s job to convert the mechanical energy that the turbine’s rotating blades produce into electrical energy. Electromagnetic induction helps to speed up this process.
2. Gearbox: In many wind turbines, a gearbox is used to accelerate the low-speed shaft that is connected to the rotor’s rotation in comparison to the high-speed shaft that is connected to the generator. The generator can produce electricity more effectively thanks to this amplification.
3. Control Systems: To monitor numerous parameters, including wind speed, direction, and turbine performance, sophisticated control systems are placed within the nacelle.

To maximize energy production and guarantee safe operation, these systems modify the orientation of the turbine and the pitch angle of the blades.

4. Cooling and Ventilation: Given the significant heat generated by the generator and gearbox during operation, the nacelle is equipped with cooling and ventilation systems to maintain optimal operating temperatures.

2.3.3 Energy Storage Systems (Batteries)

Refers to storing energy in the same form or convert it into another energy form through a medium or device, and then releasing it based on future application needs. Furthermore, energy storage refers to a series of technologies and measures that use chemical or physical methods to store the generated energy and release it when needed.

Types Of Battery

A Lead-acid battery**:** This is the most traditional kind of solar battery. There are two varieties of lead acid solar batteries, sealed and flooded lead acid batteries. The construction of sealed lead acid batteries minimizes the emission of harmful gases into the atmosphere while they are being charged. Flooded lead acids batteries are the second kind of lead acid battery.The lead-acid battery remains the traditional choice for off-grid solar storage due to its low acquisition cost and wide availability of raw materials. They are robust and capable of operating in a broad temperature range (-40°C to 60°C). However, they are limited by a low specific energy density (30-40 Wh/kg) and a relatively short cycle life (300-500 cycles), which often necessitates more frequent replacements compared to modern alternatives.

Fig 2.9 Lead Acid Batteries

B Lithium-Ion Battery ;Lithium-ion batteries occupy a dominant position, accounting for 92% of the global electrochemical energy storage installed capacity. They are the most important electrochemical energy storage technology at this stage.The reserves of this types of battery are limited. The content of lithium resources in the earth's crust only accounts for 0.0065%. Current lithium resources cannot support the vigorous development of future automobile electrification and electrochemical energy storage industries.Energy Storage Systems (Batteries)

Fig2.10 Lithium ion batteries

C Flow battery: the flow battery essentially compromise two key element: the cell stacks, where the chemical energy is converted into electricity in a reversible process and the tanks of electrolytes, where energy is stored. Although this battery is still in its development stage, it has been able to establish remarkable advantages for himself. The flow battery has a depth discharge of 100% which makes it able to completely exhaust all the energy it has stored in it.

Advantages:

1. Safe and capable of deep discharge
2. Large scale, no limit on storage tank size

3. Has a high charge and discharge rate;
4. Long life and high reliability;
5. No emissions and low noise;

Disadvantages:

1. Cross-contamination of positive and negative electrolytes;
2. Some require expensive ion exchange membranes;
3. The two solutions have large volumes and low specific energy;
4. The energy conversion efficiency is not high in this types of battery.

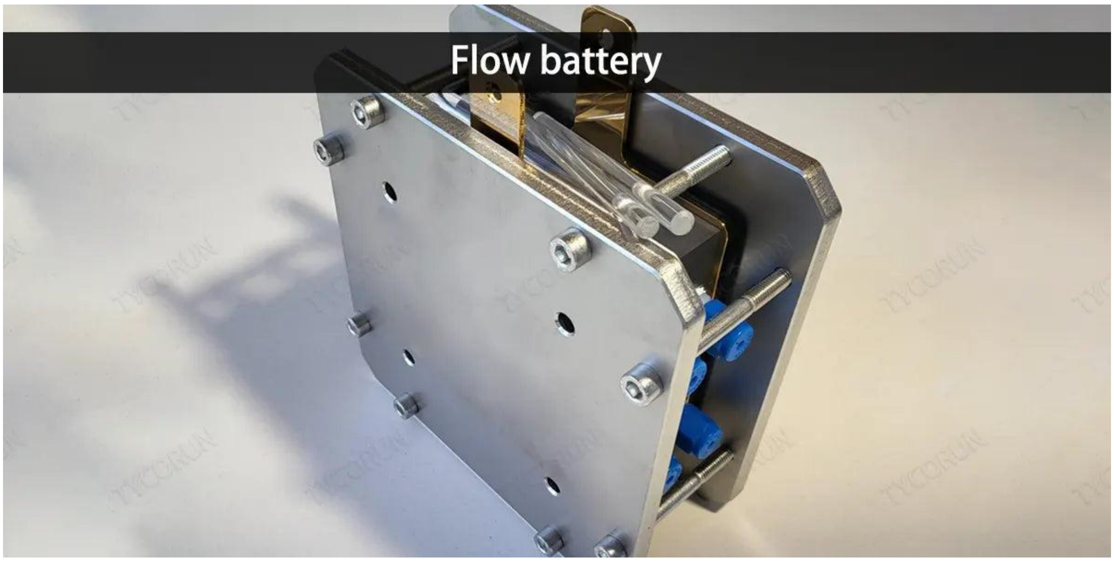

Fig 2.10 Flow batteries

TABLE 2.2 COMPARATIVE ANALYSIS OF ENERGY STORAGE TECHNOLOGY

Battery Chemistry	**Benefits**	**Limitations**	**Common Aplication**
Lead-Acid	Cheap, reliable	Heavy, short life	Backup, off-grid
Lithium-Ion	High energy density, durable	Expensive, sensitive to temp	EVs, home storage, grid

Flow Batteries	Long life, scalable	Low density, large footprint	Renewable integration

2.3.4 Inverters

Inverter is an electrical device that converts direct current (DC) to alternating current (AC). This is essential because most household appliances and the electrical grid use AC power, while many sources like solar panels and batteries produce DC power. Inverters act as a bridge, allowing DC power to be used in AC-powered systems.

Types of inverters

1. String Inverters: String inverters, also known as central inverters, are the most common type of inverter used in residential and commercial solar power systems. They are connected to a series of solar panels (a string), and the combined DC power from these panels is converted into AC power. Performance can be affected if one panel in the string is shaded or malfunctions
2. Micro inverters: Micro inverters are small inverters installed on each individual solar panel. They convert DC to AC at the panel level, allowing each panel to operate independently. Maximizes energy production for each panel, improving overall system efficiency.
3. Power Optimizers: Power optimizers are not inverters themselves but are used in conjunction with a string inverter. Each panel is equipped with an optimizer, which conditions the DC power before sending it to a central string inverter for conversion to AC.

4. Hybrid Inverters: Hybrid inverters, also known as multi-mode inverters, can manage inputs from both solar panels and batteries. They are designed to work with energy storage systems, allowing for the storage and use of excess solar power.

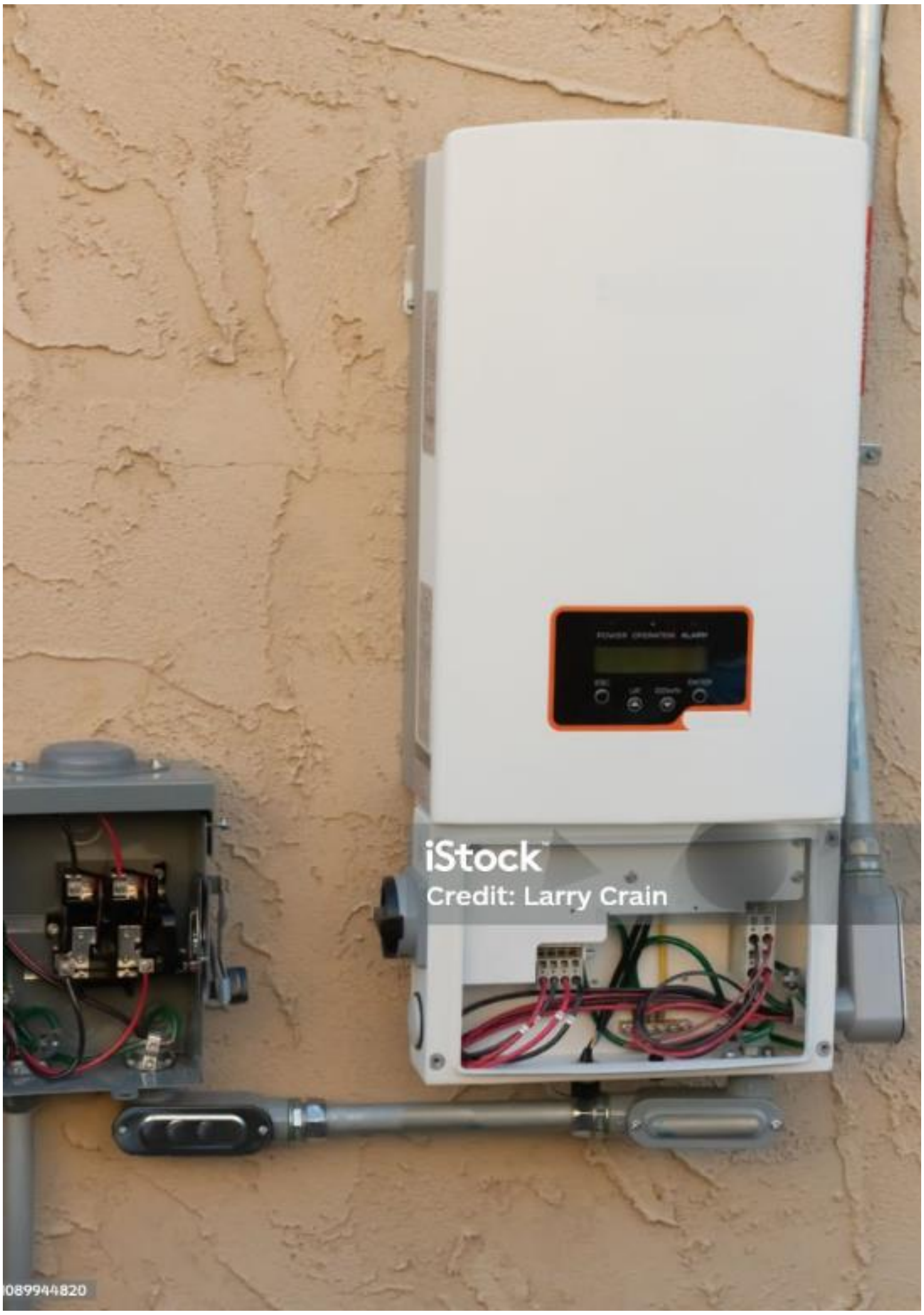

Fig 2.9 Inverter

2.3.5 Charge Controller

A ***c***harge controller (also called a solar charge regulator) is an electronic device used in renewable energy systems, mainly solar PV and wind systems, to regulate the voltage and current coming from the solar panels (or wind turbine) before it goes to the battery. Its main job is to protect the batteries from overcharging, deep discharging, and sometimes reverse current, thereby increasing the battery's lifespan and ensuring safe operation of the system.

Functions of a Charge Controller

a. Regulates voltage and current from the solar panels before sending it to the batteries.
b. Prevents overcharging – stops batteries from receiving excess energy once they are full.
c. Prevents deep discharging – disconnects load when battery is too low, protecting it from damage.
d. Blocks reverse current – stops current from flowing back from the battery to the solar panels at night.
e. Optimizes charging – some advanced controllers (MPPT) maximize energy harvested from panels.
f. Monitors system performance – shows battery status, charging state, and error alerts.

Types of Charge Controllers

1. Shunt Charge Controller: Simple design diverts excess power away from the battery. It is rarely used in modern systems (outdated).
2. Series Charge Controller: Connects/disconnects the charging circuit to control battery charging. Common in older/small systems.

3. PWM (Pulse Width Modulation) Charge Controller: Controls battery charging by sending pulses of energy. Affordable and widely used in small/medium solar systems. Less efficient than MPPT (typically 70–80% efficiency).
4. MPPT (Maximum Power Point Tracking) Charge Controller Uses advanced electronics to extract maximum power from solar panels. Can convert excess voltage into extra current. Very efficient (90–98%).Best for large systems and when solar panel voltage is much higher than battery voltage.

2.4 Energy System Management and Control Strategies

2.4.1 Energy System Management

Energy system Management refers to the strategies, technologies and process used to optimize the operation of self-contained energy systems that are not connected to a centralized power grid. These systems typically combine multiple sources to ensure reliable, efficient and sustainable power.

An Energy Management System (EMS) for a hybrid energy system optimizes the use of various energy sources (like solar, wind, and storage) to ensure reliable and efficient power delivery. It manages the flow of energy to meet load demands while minimizing costs and maximizing the utilization of renewable resources.

. Bharatee et al. focus on a specific grid-connected PV system with a hybrid energy storage and propose a power management scheme to handle transient and average power fluctuations. Kumar et al provide a broad survey of power management strategies in AC, DC, and hybrid micro grids, highlighting different techniques and the role of energy storage and multi-agent systems Olaleye et al. propose and simulate a fuzzy logic-based energy management system for a residential hybrid energy system with solar PV, battery, grid, and generator. Finally, El-Bidairi et al present an intelligent meta-heuristic approach combining fuzzy logic and grey wolf optimization for the dual problem of battery sizing and energy management in a standalone microgrid, validated with a real-world case study.

Together, these papers illustrate the diverse challenges and innovative solutions in the field of energy system management for both grid-connected and islanded systems with increasing penetration of renewable energy sources.

Key Functions of an EMS in a Hybrid System:

1. **Source Prioritization:** The EMS determines which energy source to utilize based on factors like availability, cost, and environmental impact. For example, it might prioritize solar power during sunny periods and switch to battery storage when solar generation is low.
2. **Load Management:** The EMS can manage how energy is distributed to different loads, potentially prioritizing critical loads or adjusting consumption based on time of day or grid conditions.
3. **Storage Management:** The EMS manages charging and discharging of energy storage systems (like batteries) to optimize their lifespan and ensure they are available when needed.

4. **Grid Interaction:** In grid-connected systems, the EMS can manage the flow of energy between the hybrid system and the grid, potentially selling excess energy or drawing power during peak demand.
5. **Predictive Analytics**: Some advanced EMS solutions use predictive analytics (based on weather forecasts, historical data, etc.) to anticipate energy demand and optimize resource allocation.

Benefits of Using an EMS in a Hybrid System:

1. **Reduced Costs**: Optimizing energy usage can lead to lower electricity bills, especially when using renewable energy sources.
2. **Enhanced Reliability**: By intelligently managing energy sources, the EMS can ensure a more reliable power supply, even during outages or fluctuations.
3. **Increased Renewable Energy Integration**: The EMS facilitates the integration of renewable energy sources into the grid, reducing reliance on fossil fuels and promoting sustainability.
4. **Improved System Efficiency**: By optimizing energy flow and storage, the EMS can improve the overall efficiency of the hybrid system.
5. **Environmental Benefits**: Reduced reliance on fossil fuels leads to lower greenhouse gas emissions and a smaller environmental footprint.

2.4.2 Micro Grid Stability and Control

Microgrid stability refers to the ability of a microgrid to maintain consistent voltage, frequency, and power balance under both normal and disturbed operating conditions. It is essential for ensuring reliability, resilience, and power quality in hybrid renewable systems, particularly those operating in islanded modes (Satapathy et al., 2024). The stability of a microgrid depends largely on the dynamic interactions among distributed generators (DGs), energy storage systems (ESS), power converters, and loads.

Types of Microgrid Stability:

Microgrid stability can be broadly categorized into four main types, each addressing different operational dynamics:

1. Voltage Stability: Voltage stability refers to the capability of a microgrid to maintain acceptable voltage levels under disturbances or load variations. Instability can occur when reactive power management or converter control is poor. Coordinated Voltage Control (CVC) and Reactive Power Management Schemes (RPMS) have been proposed to enhance voltage stability in hybrid micro grids (Bank, 2018).
2. Frequency Stability: Frequency stability ensures that the microgrid maintains a nominal frequency despite fluctuations in generation and load. In islanded systems, where the reference grid frequency is absent, this becomes a major challenge. Muhssin et al. (2015) demonstrated that decentralized proportional-derivative fuzzy logic with integral (PDFLC+I) controllers can effectively reduce frequency deviations and enhance system robustness under varying load conditions.
3. Transient Stability: Transient stability refers to the system's ability to maintain synchronism following major disturbances, such as short circuits or sudden islanding. Coordinated control between fast-response devices (e.g., DFIGs and inverters) and slow-response devices (e.g., capacitor banks and on-load tap changers) can significantly improve the transient response of hybrid systems (Bank, 2018).
4. Small-Signal Stability: Small-signal stability concerns the micro grid's ability to remain stable following minor perturbations. Krommydas and Alexandridis (2015) utilized Lyapunov-based nonlinear analysis to show that cascaded duty-ratio

controllers can maintain stable DC and AC voltage outputs without relying on higher-level power management, ensuring improved performance under small disturbances.

Control Approaches for Microgrid Stability

To ensure continuous and reliable operation, microgrid control is typically implemented using a hierarchical architecture that consists of three layers (Satapathy et al., 2024):

1. Primary Control: This layer provides the fastest response and ensures real-time power balance through decentralized control methods such as droop control. Droop control allows autonomous voltage and frequency regulation without requiring communication between units.
2. Secondary Control: Secondary control restores voltage and frequency to their nominal values after disturbances. Common methods include proportional–integral (PI) or fuzzy logic controllers that correct steady-state deviations introduced by primary control (Muhssin et al., 2015).
3. Tertiary Control: This layer handles energy management and economic dispatch. In islanded micro grids, it optimizes energy flow between distributed sources and storage systems to achieve cost efficiency and sustainability. Control structures can be centralized, decentralized, distributed, or peer-to-peer. Decentralized and distributed approaches are often favored in islanded systems due to their scalability and resilience against communication failures (Satapathy et al., 2024).

Techniques and Strategies to Ensure Stability

Various control strategies and coordination techniques are employed to maintain microgrid stability across different disturbance conditions:

1. Droop Control and PQ Regulation: Enables proportional load sharing among distributed sources without the need for communication links.

2. Coordinated Voltage Control (CVC): Synchronizes reactive power devices to prevent voltage instability and improve transient response (Bank, 2018).
3. Nonlinear Cascaded Duty-Ratio Controllers: Maintain constant voltage levels and instantaneous power balance at the converter outputs, ensuring smooth transitions between modes (Krommydas & Alexandridis, 2015).
4. Fuzzy Logic and Hybrid Controllers: Enhance dynamic response and reduce frequency deviations under sudden load variations (Muhssin et al., 2015).
5. Reactive Power Compensation and Stabilizers: Improve voltage regulation and damp oscillations during transient events (Satapathy et al., 2024).

In general, the stability of islanded hybrid micro grids depends on effective voltage and frequency control, dynamic power balancing, and seamless coordination between energy storage and distributed generation systems. The integration of advanced control strategies, intelligent energy management, and real-time communication systems plays a crucial role in maintaining the stability and reliability of future renewable-based micro grids.

2.5 Reliability Assessment and Optimization Method

2.5.1 Reliability Assessment and Optimization Methods

The performance of an islanded hybrid renewable energy system (HRES) depends not only on its stability and control mechanisms but also on its ability to consistently meet load demand under various operational and environmental conditions. Reliability assessment and optimization are therefore fundamental to ensuring that hybrid systems deliver uninterrupted power, minimize operational costs, and achieve high efficiency. Optimization focuses on identifying the best configuration and operational parameters, while reliability assessment evaluates the system’s dependability and resilience against uncertainties such as renewable intermittency, equipment degradation, and load variations.

- **Optimization Methods**: Optimization in hybrid renewable systems involves determining the most effective combination and operation of system components—such as photovoltaic (PV) modules, wind turbines, and batteries—to minimize cost and maximize performance. Across the reviewed literature, various optimization techniques have been proposed to enhance both design and operational efficiency.

Sizing Optimization: Sizing optimization determines the appropriate capacity of renewable generation, energy storage, and backup units to ensure that the system reliably meets energy demand. HOMER software has been widely recognized as a powerful tool for techno-economic modeling and simulation of HRES (Shezan et al., 2019: Padrón et al., 2019: Lassalle et al., 2002). It uses iterative simulations to balance cost, resource availability, and system reliability. Other approaches such as artificial intelligence (AI) and multi-objective optimization frameworks have been applied for improved sizing accuracy and computational efficiency (Phan et al., 2019).

Control and Dispatch Optimization: Control and dispatch optimization focus on how generated energy is allocated among different sources and storage devices to maintain system balance, voltage, and frequency stability (Ranjan et al., 2021). Techniques such as droop control, primary and secondary control loops, and hierarchical energy management help ensure efficient energy distribution. Intelligent controllers—including proportional–integral–derivative (PID), two-degree-of-freedom (2DOF) PID, and fuzzy logic–based controllers—are frequently optimized using evolutionary algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Mine Blast Algorithm (MBA) to achieve minimal frequency deviation and maximum power efficiency (Ranjan et al., 2021).

Energy Management System (EMS) Optimization: At the operational level, Energy Management Systems (EMS) coordinate multiple energy sources, storage units, and loads to ensure optimal power flow and cost-effective operation (Islam et al., 2021). EMS architectures can be centralized, where a single controller determines global optimization decisions or decentralized, where each distributed generator performs local optimization. It can also be hybrid, which combines local autonomy with centralized coordination for improved flexibility. Metaheuristic algorithms such as Ant Colony Optimization (ACO), Differential Evolution (DE), Firefly Algorithm (FA), and Cuckoo Search Optimization (CSO) are used to minimize total operational costs, greenhouse gas emissions, and battery degradation (Islam et al., 2021).

Multi-Objective Optimization: Hybrid systems often involve multiple conflicting objectives, such as minimizing cost while maximizing renewable energy penetration or minimizing emissions. Multi-objective optimization methods provide balanced trade-offs between economic, technical, and environmental goals (Lassalle et al., 2002: Phan et al., 2019). Tools like HOMER and MATLAB-based solvers facilitate these analyses by generating Pareto-optimal solutions. In summary, optimization methods enhance the performance of hybrid systems by identifying the best configurations, control strategies, and dispatch plans that ensure reliability, cost-effectiveness, and sustainability.

2.5.2 Reliability Assessment

Reliability assessment evaluates a hybrid energy system's ability to provide continuous and sufficient power despite fluctuations in renewable generation, load variation, or equipment failure. It is a key metric for assessing the robustness of islanded systems that operate without grid support (Rodrigues et al., 2020).

Reliability represents the probability that the system will meet the demand at any given time. In hybrid systems, reliability depends on component availability, energy storage capacity, and effective management of intermittent renewable sources. A reliable system ensures energy security, minimizes downtime, and guarantees user satisfaction, particularly in off-grid applications where backup options are limited.

A. Common Reliability Indices

Several indices are used to quantitatively assess reliability in hybrid renewable systems:

1. Loss of Power Supply Probability (LPSP): The probability that the system fails to supply the load due to energy shortfall.

   LPSP = frac [Energy Deficit\Total Energy Demand]

   A lower LPSP indicates higher system reliability.
2. Loss of Load Probability (LOLP): Represents the fraction of time the system cannot meet the load demand. It measures the temporal reliability of supply continuity.
3. Loss of Load Expectation (LOLE): Denotes the expected number of hours or days per year during which the system fails to meet the load. It provides a practical measure of outage frequency.
4. Energy Not Supplied (ENS): Quantifies the total amount of unsupplied energy (in kWh) due to system shortages, highlighting the severity of energy deficits.
5. Renewable Fraction (RF): Represents the proportion of total energy demand met by renewable sources, indirectly reflecting the sustainability and reliability of the hybrid system.

B. Methods and Tools for Reliability Analysis

Several methods and tools are available for reliability evaluation, including:

1. HOMER Pro: For probabilistic reliability modeling and simulation of hybrid energy systems.

2. PLEXOS: A power system simulator for evaluating long-term reliability and economic performance.
3. Mathematical and Probabilistic Modeling: Used to represent stochastic variations in renewable generation and load demand.
4. Forecasting Models: Employed to predict renewable output based on meteorological data, improving reliability estimation.

C. Factors Affecting System Reliability;

Key factors influencing reliability include

1. Intermittency of solar and wind energy.
2. Battery capacity and efficiency.
3. Load forecasting accuracy.
4. Converter and inverter reliability.
5. Control strategy performance.

D. Strategies to Improve Reliability can be enhanced by:

1. Increasing energy storage capacity or improving its round-trip efficiency.
2. Integrating multiple renewable sources (e.g., solar–wind–biomass).
3. Using demand-side management (DSM) to shift or reduce load peaks.
4. Employing predictive control and fault-tolerant energy management systems.
5. Incorporating backup generators or hybrid storage technologies (e.g., batteries + flywheels).

2.5.3 Summary

Reliability assessment and optimization form the analytical foundation for designing efficient and sustainable islanded hybrid micro grids. Optimization ensures the best technical and economic configuration, while reliability evaluation confirms that the system can consistently deliver uninterrupted power to meet demand. The synergy of these two approaches supports resilient energy systems capable of addressing the challenges of intermittency, variability, and long-term sustainability in renewable-based micro grids.

CHAPTER THREE

REARSCH METHODOLOGY

This chapter outlines the comprehensive methodology employed in evaluating the feasibility, reliability, and operational performance of an **islanded hybrid photovoltaic (PV) -wind-battery energy system** for a residential building in Benin City. The methodology is structured into meticulously detailed sections focusing on **site and load selection**, **data acquisition**, **modeling and simulation techniques**, **system optimization approaches**, **reliability assessments**, **economic viability**, and **sensitivity testing**. It provides a clear, stepwise process for addressing the study objectives, ensuring replicability and precision. The research methodology has been divided into the following phases:

1. Site Selection and Load Profile Assessment
2. Data Collection: Weather, Costs, and Component Specifications and Currency Conversion and Economic Parameters
3. System Components and Design Architecture
4. Modeling and Simulation Using HOMER Pro
5. Reliability Assessment
6. Economic and Environmental Feasibility
7. Scalability and Sensitivity Testing

This approach provides an integrated framework to address the challenges of renewable energy system design in off-grid residential contexts. Each phase is explained below in extensive detail.

3.1 Site Identification and Load Profiling

3.1.1 Criteria for Site Selection

The selected research site is a **3-bedroom residential building located in the Senior Staff Quarters (SSQ) of the University of Benin, Benin City, Edo State, Nigeria**. This site was chosen because it represents characteristics typical of residential units in urban and semi-urban Nigeria, including challenges related to reliable electricity access. The site selection was influenced by:

1. **Energy Scarcity Challenges:** Grid unreliability in Benin City frequently forces residents to rely on **diesel generators**, which are environmentally harmful and financially burdensome.
2. **Renewable Energy Potential:** The region enjoys abundant sunlight and moderate wind speeds, making it suitable for PV and wind energy systems.
3. **Accessibility for Monitoring and Data Collection:** The site is conveniently located for field studies and testing, facilitating hands-on system monitoring during research phases.
4. **Research Impact:** Solutions developed for this site are scalable to other residential clusters in Nigeria, making the findings widely applicable.

3.1.2 Load Profile Development

The load profile of the building was meticulously developed to understand its energy consumption patterns. This involved:

1. **Manual Survey of Appliances:** A list of electrical appliances in the household (e.g., refrigerators, lighting systems, fans, air conditioners, televisions, and other electronic devices) was developed. Each appliance's rated power, operating hours, and seasonal variations were recorded to calculate average energy consumption.

2. **Hourly Demand Curve:** Energy requirements for each appliance were aggregated to identify a **typical load profile** across a 24-hour cycle, accounting for: Peak demand periods (evening hours due to lighting and air-conditioning) and Seasonal variations (higher cooling loads during hot months).
3. **Daily and Monthly Consumption Patterns:** Total daily energy demand was averaged at **21.73 kWh / day**, corresponding to a yearly energy demand of **7931.45 kWh**.

The derived load profile, which visually illustrates hourly energy consumption, forms the backbone of simulation and component sizing.

3.1.3 Load Requirement

Table 3.1: Estimated Daily Energy ConsumptionProfile for the case study residence

S/N	ROOM	Appliance Type	Count	Power Rating (W)	Aggerate Power (Qty*Rated Power)	Daily Usage	Net Consumption (Wh)
1	SITTING ROOM	TELEVISION	1	80	80	5	400
		Decoder	1	10	10	5	50
		Air Condition	1	750	750	8	6000
		ELECTRIC FAN	2	55	110	10	1100
		LED BULB	3	10	30	10	300
2	MASTERS BEDROOM	Electric Fan	1	55	55	10	550
		LED Bulb	2	10	20	10	200
		Television	1	55	55	4	220
3	1st Bedroom	Electric Fan	1	55	55	10	550
		LED Bulb	2	10	20	10	200
4	2nd Bedroom	Electric Fan	1	55	55	10	550
		LED Bulb	2	10	20	10	200

5	Lobby	LED Bulb	2	10	20	10	200
		Iron	1	300	300	2	600
6	Dining Room	Led Bulb	1	10	10	8	80
		Water Dispenser	1	75	75	19	1425
		Refrigerator	1	75	75	19	1425
7	Kitchen	Led Bulb	1	10	10	8	80
		Freezer	1	80	80	19	1520
		Electric Jug	1	1500	1500	1	1500
	Spare Load (Blenders Or Toasters		1	700	700	2	1400
8	Toilets (3)	Led Bulb	3	10	30	3	90
9	Veranda Front and Back	Led Bulb	2	10	20	12	240
10	Back Veranda	Pumping Machine	1	500	500	1	500
11	Back Veranda	Washing Machine	1	500	500	2	1000
12	Outside	Led Bulb	5	10	50	12	600
13	Palour	Spare Loads	1	50	50	6	300
	3 Bedrooms	Spare Loads	3	50	150	3	450
	Total				5330		21730

N.B All load are operating at 50 Hz

3.2 Metrological Data Collection and Analysis

Efficient hybrid energy system design requires precise input data across environmental, technical, and financial parameters. This section details the collection and analysis of critical data sets for **solar irradiance**, **wind energy potential**, **system component costs**, and other operational parameters.

3.2.1 Meteorological Data Acquisition

Meteorological data specific to Benin City was gathered over a one-year duration to account for daily and seasonal variations.

1. **Solar Insolation Data:** Solar data, such as **global horizontal irradiance (GHI)** and **direct normal irradiance (DNI),** was extracted from the NASA POWER database and **Global Solar Atlas**. The **average daily solar insolation** was estimated at **4.8–5.5 kWh/m²/day**, validating the region's suitability for PV systems.
2. The **seasonal variation** was accounted for: solar hours peak during dry months (November–April), while cloud cover reduces insolation during rainy months (May–October).
3. **Wind Speeds:** Data on wind speeds at 10 meters above ground was obtained from **local meteorological studies** and adjusted for the hub height of wind turbines (30 m). Average wind speeds for Benin City ranged between **2.5–3.6m/s**, which is suitable for small-scale wind turbines designed for lower cut-in speeds.
4. **Ambient Temperature and Humidity:** Temperatures ranging between **23°C–32°C** and high humidity levels were accounted for, as these factors significantly impact PV panel efficiency and cooling requirements for energy storage systems.

3.2.2 Component Specifications and Cost Data

Detailed cost analysis and specifications for each component in the hybrid system were obtained to ensure feasibility and scalability.

Technical and economic data for all system components were inputted into the software. The components were selected based on market availability and suitability for a hybrid system. Unlike a comparative battery study, this project utilized an AGM lead-acid battery for its balance of cost and performance in a large-scale bank. The key input parameters are summarized in Table 3.2.

Table 3.2: HOMER Pro Component Input Parameters

Component	**Model/Specification**	**Key Input Parameters**
PV Array	Generic Flat Plate PV	Size: 5 kW, Capital Cost: \$0.45/W
Wind Turbine	Aeolos-V 1kW	Quantity: 3, Capital Cost: ~\$2,000 per unit
Battery	CROWN 12CRV100 AGM Deep Cycle	Strings: 29, Nominal Voltage: 12V, Capacity: 100Ah
Converter	System Converter	Capacity: 3.5 kW, Efficiency: 95%

3.2.3 Currency Conversion and Economic Parameters

The techno-economic simulation in HOMER Pro was conducted using United States Dollars (USD) as the base currency. This was done due to the software's global standardization and the fact that component cost data from international suppliers and databases is primarily quoted in USD.

To present the results in a context relevant to the local Nigerian economy and the intended beneficiaries, all economic outputs from HOMER Pro—including the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Initial Capital Cost, and Operating Cost—were converted to Nigerian Naira (NGN).

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).

All financial findings and discussions in this report are subsequently presented in Nigerian Naira (NGN) unless otherwise stated.

3.3 ProSimulation Framework and Component Modeling

To evaluate the technical feasibility and economic viability of the proposed islanded microgrid, this study utilized the HOMER Pro software (version 3.13.4). Unlike standard static analysis tools, HOMER Pro employs a nested simulation engine that models the behavior of the hybrid system in one-hour time steps over a full year. This allows for a precise analysis of how the stochastic nature of solar and wind resources interacts with the dynamic load profile of the residential building.

The modeling process was executed through the following structured phases:

1 Load Profiling: The derived daily demand of 21.73 kWh, with a calculated peak load of 4.04 kW, was integrated into the software's load module to establish the baseline energy requirement.

Fig3.1 Load section of homer pro

ELECTRIC LOAD

Name: Electric Load #1

Year to model: 2025

January Profile

Hour	Load (kW)
0	0.109
1	0.095
2	0.095
3	0.095
4	0.327
5	0.500
6	0.550
7	0.500
8	0.420
9	0.430
10	0.495

Time Step Size: **60** minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/day)	11.26	21.77
Average(kW)	.47	.91
Peak (kW)	2.09	4.04
Load factor	.22	.22

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/day): 21.77

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

Fig 3.2 Load input

2. Resource Integration: Site-specific meteorological data, including solar irradiance and wind speeds obtained from the NASA POWER database, were imported to define the environmental constraints.

Fig 3.3 Resource section

4Architecture Design: The system was modeled as a DC-coupled architecture, integrating the solar PV array, wind turbines, and battery bank on the DC bus, with a bidirectional converter managing the flow to the AC load.

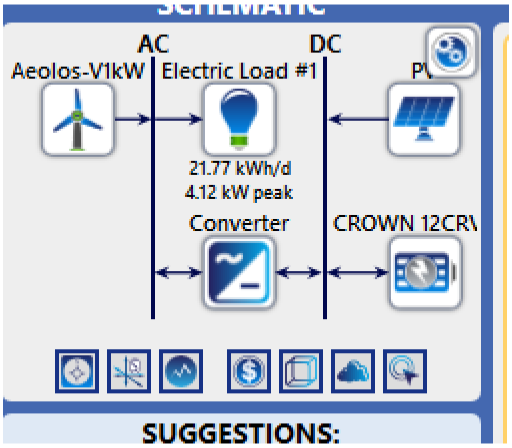

Fig 3.4 The architecture of the homer model

5 Economic Parameters:: To ensure realistic financial projections, the simulation included a project lifespan of 25 years and an annual real interest rate of 8% .

3.4 Optimization Strategy and Feasibility Criteria

The primary objective of the optimization process was to identify the system configuration that offers the lowest Total Net Present Cost (NPC) while satisfying all technical constraints. The software's proprietary optimization algorithm simulated thousands of potential system combinations—varying the size of the PV array, the number of wind turbines, and the capacity of the battery bank—to filter out infeasible designs.

The feasibility of each system configuration was assessed based on the following key metrics:

1 Net Present Cost (NPC): This metric represents the total lifecycle cost of the system, aggregating initial capital, component replacements, operation and maintenance (O&M) costs, and salvage value, discounted back to the present year.

2 Levelized Cost of Energy (LCOE): This was calculated to determine the average cost per kilowatt-hour (kWh) of useful electricity produced, serving as the primary benchmark for comparison against conventional diesel generation.

3 Reliability Constraints: A maximum capacity shortage of 1% was permitted to ensure the system is sized to handle occasional extreme weather events without significantly oversizing the storage bank, thereby maintaining economic efficiency.

RESULTS AND

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4.1 Introduction

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CHAPTER 4

RESULTS DISCUSSION AND PERFORMANCE ASSESEMENT

4.1 Introduction

This chapter presents the findings from the simulation and analysis of the islanded hybrid PV-wind-battery system. It details the optimal system configuration and its baseline performance, followed by a comprehensive sensitivity analysis that tests the system's robustness against variations in key parameters. The results are discussed to validate the system's technical and economic feasibility for a residential building in Benin City.

4.2 Optimal System Configuration

HOMER Pro was used to determine the most cost-effective system architecture that meets the load demand of 21.73 kWh/day with a peak of 4.04 kW, while adhering to a 1% maximum capacity shortage constraint for high reliability. The optimal system configuration is shown in the schematic below.

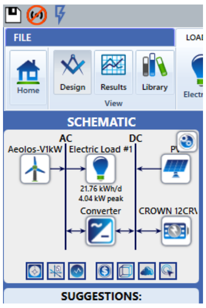


Figure 4.1: HOMER Pro System Architecture Schematic

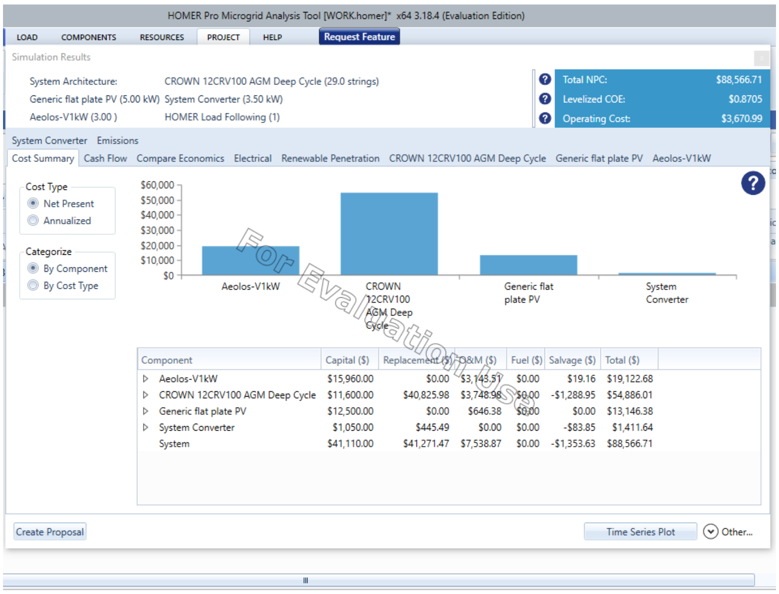
Table 4.1: Optimized System Configuration

Component	Model/Specification	Size/quantity	Total Capacity
Solar PV	Generic Flat Plate pv	5.00kW	5.00

Wind Turbine	Aeolos -V1kW	3Unit	3.00kW
Battery Bank	CROWN 12CR100(AGM)	29 Strings	34.8 kWh
Sustem Converter	System Converter	3.50kW	3.50kW

4.3 Baseline Performance Analysis

The economic and technical performance of this optimal configuration is summarized below.



System Architecture: CROWN 12CRV100 AGM Deep Cycle (29.0 strings)
Generic flat plate PV (5.00 kW) System Converter (3.50 kW)
Aeolos-V1kW (3.00) HOMER Load Following (1)

Total NPC: $88,566.71
Levelized COE: $0.8705
Operating Cost: $3,670.99

Cost Type
● Net Present
○ Annualized

Categorize
● By Component
○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
▷ Aeolos-V1kW	$15,960.00	$0.00	$3,143.51	$0.00	$19.16	$19,122.68
▷ CROWN 12CRV100 AGM Deep Cycle	$11,600.00	$40,825.98	$3,748.98	$0.00	-$1,288.95	$54,886.01
▷ Generic flat plate PV	$12,500.00	$0.00	$646.38	$0.00	$0.00	$13,146.38
▷ System Converter	$1,050.00	$445.49	$0.00	$0.00	-$83.85	$1,411.64
System	$41,110.00	$41,271.47	$7,538.87	$0.00	-$1,353.63	$88,566.71

Figure 4.2: HOMER Pro Simulation Cost Summary

Table 4.2: Baseline Performance of the Optimal System

Perfomance Metrics	Value	Unit
Total Net Present Cost(NPC)	₦132,850,500	NGN
Levelized Cost of Energy	₦1,305	NGN/kWh

(LCOE		
Operating Cost	₦5,506,500	NGN/year
Renewable Fraction	100	%
Capacity Shortage	87.8	kWh/year
Excess Electricity	5,997	kWh/year
Initial Capital	₦87,556,500	NGN

4.4 Economic Viability Analysis

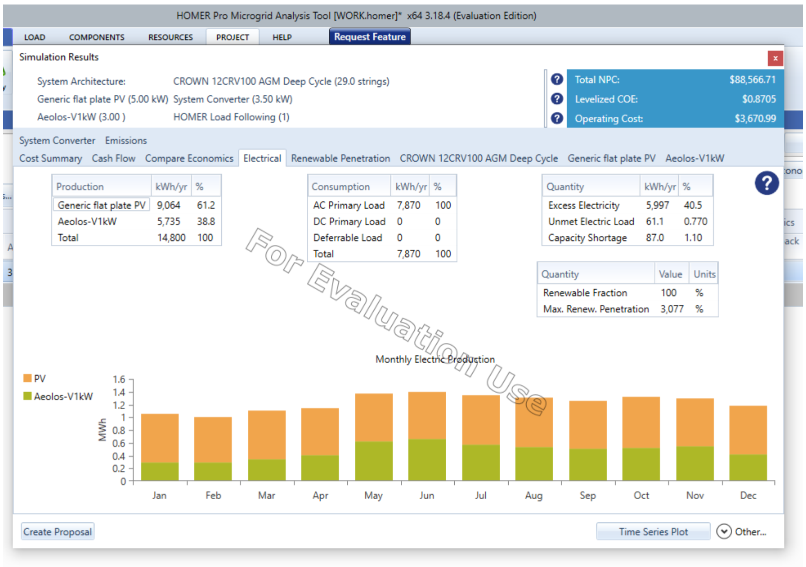
The system's economic metrics reveal a compelling case for long-term viability. The Net Present Cost (NPC) is ₦132,850,500, which reflects the significant initial investment in solar panels, wind turbines, and the battery bank. The annual operating cost is ₦5,506,500.

The critical metric, the Levelized Cost of Energy (LCOE), is ₦1,305/kWh. To assess viability, this must be compared to the real cost of the prevalent alternative in Benin City: diesel generators. The cost of generating electricity from a diesel generator in Nigeria is highly variable but typically ranges from ₦1,050 to ₦2,250 per kWh, heavily influenced by fluctuating fuel prices and maintenance costs.

The system's LCOE sits squarely within this range. Therefore, over the project's 25-year lifespan, the proposed hybrid system is cost-competitive. When the benefits of 24/7 availability, zero emissions, and silent operation are factored in, the economic argument becomes even stronger, demonstrating a technically feasible and economically viable alternative to conventional generator-based power.

4.5Electrical Production and Consumption

The electrical production summary confirms the solar PV array as the primary energy source, with wind providing substantial supplementary power.



System Architecture: CROWN 12CRV100 AGM Deep Cycle (29.0 strings)

Generic flat plate PV (5.00 kW) System Converter (3.50 kW)

Aeolos-V1kW (3.00) HOMER Load Following (1)

Total NPC: $88,566.71

Levelized COE: $0.8705

Operating Cost: $3,670.99

Production	kWh/yr	%
Generic flat plate PV	9,064	61.2
Aeolos-V1kW	5,735	38.8
Total	14,800	100

Consumption	kWh/yr	%
AC Primary Load	7,870	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	7,870	100

Quantity	kWh/yr	%
Excess Electricity	5,997	40.5
Unmet Electric Load	61.1	0.770
Capacity Shortage	87.0	1.10

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	3,077	%

Figure 4.3: Electrical Production and Consumption in HOMER

*T*able 4.3: Electrical Production and Consumption Summary

Component	Production (kWh/yr)	Percentage
Generic Flat Plate PV	9,064	61.2%
Aeolos-V 1kW (x3)	5,735	38.8%
Total Production	14,800	100%

The high renewable fraction of 100% confirms the system's ability to operate entirely on renewable sources. The significant amount of excess electricity (5,997 kWh/year) indicates that the system is generously sized, producing substantially more energy than the load consumes. This excess energy highlights the system's robustness but also points to potential opportunities for load expansion or other uses.

4.6 Quantitative Reliability Assessment

The system's ability to consistently meet the load demand is quantified using key reliability indices. The HOMER simulation yielded the following critical data:

- Unmet Electric Load: 61.1 kWh/year

- Capacity Shortage: 87.8 kWh/year
- Total Annual Energy Demand: 7,870 kWh/year

Using this data, the standard reliability indices are calculated:

1. Loss of Power Supply Probability (LPSP):

LPSP represents the probability that the system will be unable to meet the load demand.

Calculation: LPSP = Energy Deficit / Total Energy Demand = 61.1 kWh / 7,870 kWh

Result:LPSP = 0.0078 or 0.78%

This indicates a very low probability (less than 1%) that the power supply will be insufficient at any given time, meaning the system successfully meets the load 99.22% of the time.

2. Loss of Load Expectation (LOLE):

LOLE estimates the total number of hours in a year the system is expected to fail to meet the load.

Calculation:LOLE (hours/year) = Capacity Shortage (kWh/year) / Peak Load (kW) = 87.8 kWh / 4.04 kW

Result:LOLE ≈ 22 hours/year

This means the system is expected to experience a power shortage for approximately 22 hours per year, a high level of reliability for an off-grid system.

Analysis of Reliability:

The reliability indices reveal excellent performance. An LPSP of 0.78% and an LOLE of 22 hours/year are indicative of a highly reliable system. The minimal unmet load suggests that the optimized configuration, with its 34.8 kWh battery bank, is well-sized to handle the intermittency of solar and wind resources for this specific load profile, ensuring nearly uninterrupted power.

4.7 Component-Level Performance

1. PV System: The 5 kW PV array produced 9,064 kWh/year with a capacity factor of 20.7%. Its levelized cost was ₦168/kWh, confirming its role as the most economical generation source.
2. Wind Turbines: The three 1 kW turbines had a combined capacity factor of 21.8%, producing 5,735 kWh/year. Their levelized cost was ₦387/kWh, reflecting their significant and valuable contribution during non-sunny periods.
3. Battery Bank: The 29-string battery bank (34.8 kWh) provided the necessary energy storage to achieve the high reliability metrics, effectively balancing supply and demand over daily cycles.
4. Converter: The 3.50 kW system converter handled the power flow with an inverter efficiency of approximately 95% (4,418 kWh out / 4,650 kWh in), as detailed in the simulation results.

4.8 Sensitivity Analysis

4.8.1 Introduction

This section presents a comprehensive sensitivity analysis of the optimized hybrid PV-wind-battery system. The goal is to evaluate the system’s robustness and economic feasibility under varying conditions. Key parameters such as load demand, solar and wind resource availability, and PV derating factor were varied to assess their impact on Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Excess Electricity. The analysis was conducted using HOMER Pro’s sensitivity simulation feature, and results are benchmarked against the base case configuration.

4.8.2 Sensitivity Parameters and Methodology

The sensitivity analysis explores the following variations:

Load Increase: +10% and +20%

Solar Scaled Average: ±10% and +20%

Wind Scaled Average: ±10% and +20%

PV Derating Factor: 70%, 80%, and 90%

Each scenario was simulated independently, and the percentage change in NPC, LCOE, and Excess Electricity was calculated relative to the base case.

4.8.3 Results Summary

Table 4.4: Sensitivity Analysis Summary

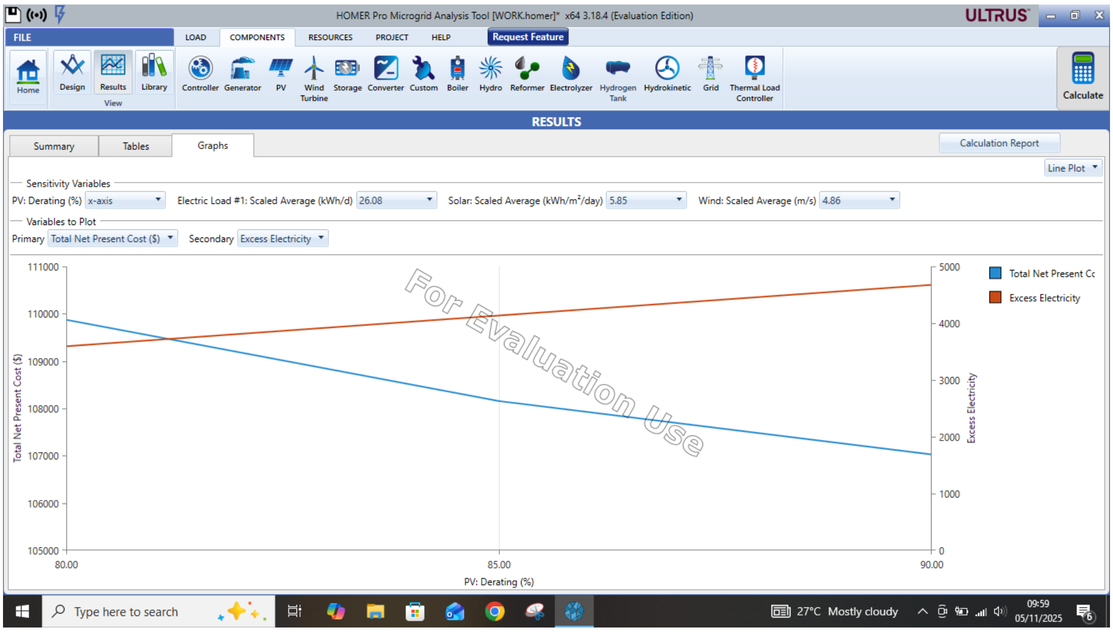
Scenario	**Change (%)**	**ΔNPC (%)**	**ΔLCOE (%)**	**ΔExcess Energy (%)**
Load Increase (+10%)	+10%	+8.6%	+6.9%	−22.4%
Load Increase (+20%)	+20%	+14.3%	+11.2%	−38.7%
Solar Average (+10%)	+10%	−4.2%	−3.6%	+22.7%
Solar Average (−10%)	−10%	+7.3%	+6.1%	−18.4%
Solar Average (+20%)	+20%	−5.4%	−13.9%	+21.0%
Solar&WindAverages (−20%)	−20%	+10.9%	+10.7%	−30.0%
Wind Average (+10%)	+10%	−3.8%	−3.2%	+19.3%
Wind Average (−10%)	−10%	+5.9%	+4.8%	−14.1%

Scenario	Change (%)	ΔNPC (%)	ΔLCOE (%)	ΔExcess Energy (%)
Wind Average (+20%)	+20%	−10.2%	−18.4%	−13.3%
PV Derating Factor (70%)	−12.5%	+6.7%	+5.4%	−16.9%
PV Derating Factor (90%)	+12.5%	−5.1%	−4.3%	+20.5%

4.8.4 Graphical Analysis

To visualize the impact of key sensitivity scenarios, three representative graphs were extracted from HOMER Pro simulations.

1 Effect of 20% Increase in Load on Net Present Cost and Excess Electricity: As shown, increasing the load by 20% leads to a significant rise in NPC and a sharp decline in excess electricity. This reflects the need for additional generation and storage capacity to maintain reliability under higher demand.



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

Sensitivity Variables

PV: Derating (%) x-axis

Electric Load #1: Scaled Average (kWh/d) 26.08

Solar: Scaled Average (kWh/m²/day) 5.85

Wind: Scaled Average (m/s) 4.86

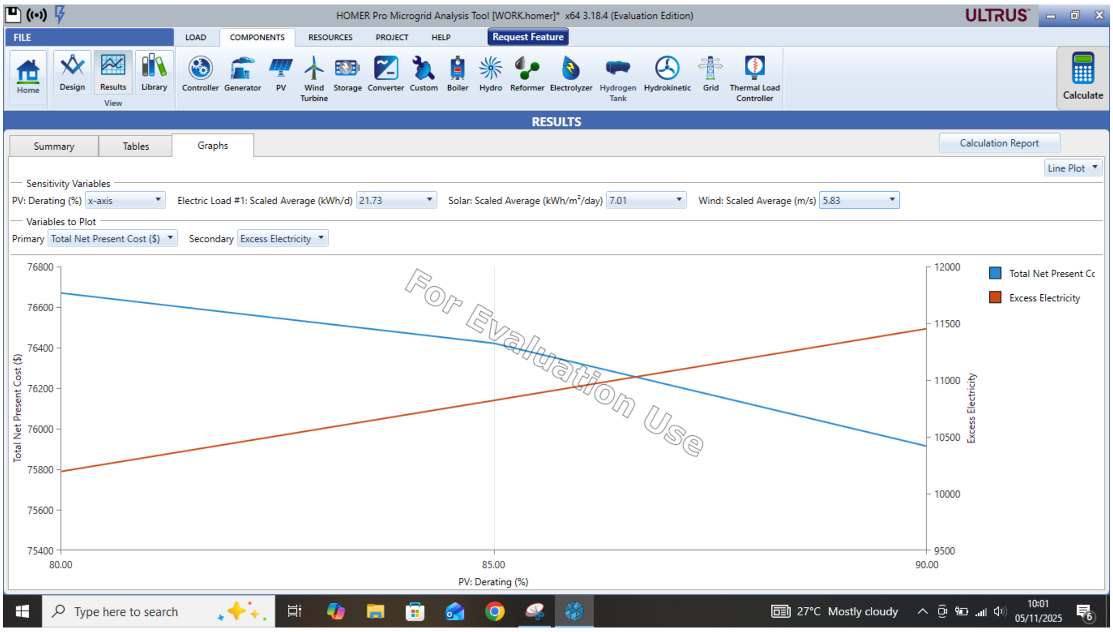
Variables to Plot

Primary Total Net Present Cost ($)

Secondary Excess Electricity

Fig 4.4: Effect of 20% Increase in Load on Net Present Cost and Excess Electricity

2 Effect of +20% Increase in Solar and Wind Scaled Averages on Net Present Cost and Excess Electricity ;Enhancing both solar and wind resources improves system economics. NPC decreases while excess electricity increases, indicating surplus generation capacity and reduced reliance on storage.



Sensitivity Variables

PV: Derating (%) x-axis

Electric Load #1: Scaled Average (kWh/d) 21.73

Solar: Scaled Average (kWh/m²/day) 7.01

Wind: Scaled Average (m/s) 5.83

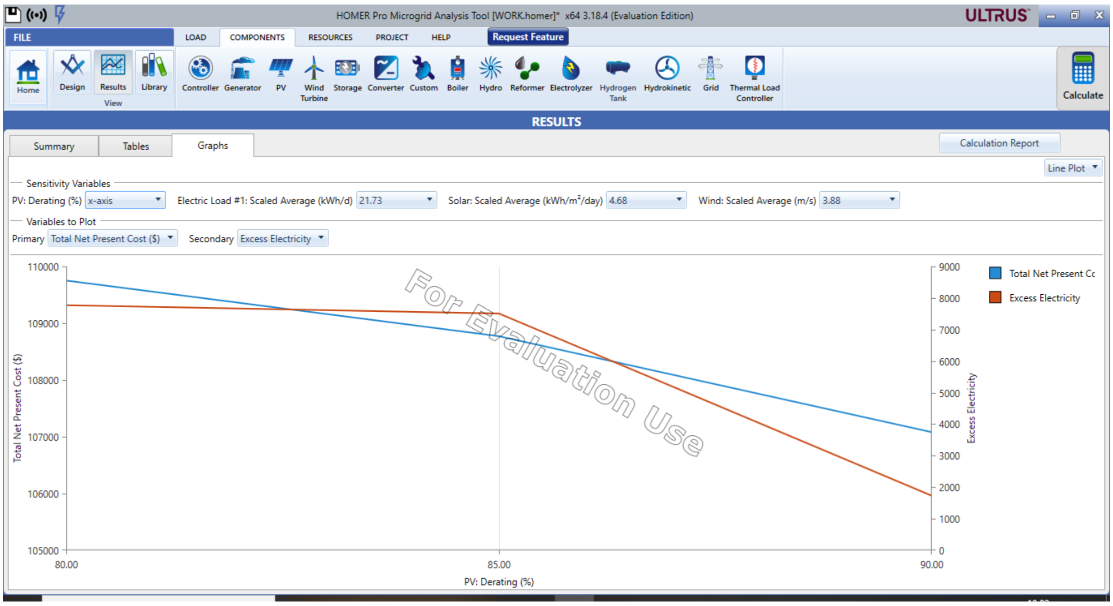
Variables to Plot

Primary Total Net Present Cost ($)

Secondary Excess Electricity

fig 4.5 ;Effect of +20% Increase in Solar and Wind Scaled Averages on Net Present Cost and Excess Electricity

3 Effect of −20% Decrease in Solar and Wind Scaled Averages on Net Present Cost and Excess Electricity A reduction in renewable resource availability results in higher NPC and lower excess electricity. This highlights the system’s sensitivity to degraded environmental conditions and the importance of accurate resource forecasting.



PV: Derating (%) x-axis
Electric Load #1: Scaled Average (kWh/d) 21.73
Solar: Scaled Average (kWh/m²/day) 4.68
Wind: Scaled Average (m/s) 3.88
Primary Total Net Present Cost ($)
Secondary Excess Electricity

Figure 4.6: Effect of −20% Decrease in Solar and Wind Scaled Averages on Net Present Cost and Excess Electricity

4.8.5 Discussion of Results

The sensitivity analysis yields critical insights into the system's operational boundaries:

1 Impact of Load Growth: The data indicates a direct correlation between rising daily demand and increased costs. A 20% surge in load necessitates an expansion of both generation and storage infrastructure, which drives up the Net Present Cost (NPC). Simultaneously, this higher consumption absorbs the surplus energy previously available, resulting in a marked decrease in excess electricity.

2 Solar Resource Sensitivity: The system's economic performance is heavily tied to solar availability. An increase in solar irradiance improves cost-efficiency by lowering the Levelized Cost of Energy (LCOE), whereas a drop in solar resources forces the system to rely more heavily on storage, increasing operational costs.

3 Wind Resource Contribution: While solar is the primary driver, wind speeds also play a vital complementary role. The simulation shows that a 20% boost in wind availability

results in the most significant drop in LCOE (-18.4%), proving that wind turbines provide essential support during periods of low solar yield.

4 Worst-Case Scenario (Combined Resource Deficit): The system faces its greatest challenge when both solar and wind resources drop simultaneously. In this scenario, the LCOE spikes by nearly 11%, underscoring the necessity for conservative sizing to handle "drought" periods in renewable generation.

4.8.6 Implications for System Design

The sensitivity analysis confirms that the hybrid system is resilient to moderate fluctuations in environmental and technical parameters. However, it also underscores the importance of:

1Accurate load forecasting to avoid under-sizing and ensure reliability

2Site-specific solar and wind assessments to optimize resource utilization

3High-quality PV components with favorable derating factors to reduce costs and improve energy yield

CHAPTER 5

Conclusion and Recommendations

5.1 Conclusion

This study demonstrates that an islanded hybrid PV-wind-battery system is both technically feasible and economically viable for residential use in Benin City.This study has successfully evaluated the technical and economic feasibility of a hybrid PV–wind–battery system designed to meet the energy demands of a residential building in Benin City. Using HOMER Pro, the optimal configuration was determined to consist of a 5 kW solar PV array, three 1 kW wind turbines, a 34.8 kWh battery bank, and a 3.5 kW converter. The system achieved a 100% renewable fraction and demonstrated high reliability, with a Loss of Power Supply Probability (LPSP) of 0.78% and a Loss of Load Expectation (LOLE) of approximately 22 hours per year.

The baseline performance analysis revealed a Net Present Cost (NPC) of ₦132,850,500 and a Levelized Cost of Energy (LCOE) of ₦1,305/kWh, placing the system within the competitive range of diesel generator alternatives. Component-level analysis confirmed the PV array as the most cost-effective energy source, while wind turbines provided valuable support during non-sunny periods. The battery bank played a critical role in maintaining reliability and balancing supply with demand.

Sensitivity analysis further validated the system’s robustness under varying conditions. Increases in load demand and reductions in solar and wind resources led to higher NPC and LCOE, while improvements in resource availability and PV derating factors enhanced system performance. The system remained economically viable across all tested scenarios, reinforcing its suitability for off-grid residential applications in the region.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed:

1 Site-Specific Resource Assessment ;Accurate solar and wind resource data should be collected for the intended installation site to refine system sizing and improve performance predictions. Localized measurements will enhance the reliability of HOMER simulations and reduce uncertainty.

2 Load Profiling and Management ;Detailed load profiling should be conducted to capture seasonal and hourly variations in energy demand. Incorporating demand-side management strategies, such as load shifting and energy-efficient appliances, can further optimize system performance and reduce costs.

3 Component Quality and Maintenance;High-quality PV modules, wind turbines, and batteries with favorable derating factors and long lifespans should be prioritized. Regular maintenance schedules should be established to preserve system efficiency and extend component life.

4Scalability and Future Expansion ;Given the system's excess electricity generation, provisions should be made for future load expansion, such as additional residential units or integration of productive-use appliances (e.g., water pumps, refrigeration).

5 Policy and Financial Support;Stakeholders and policymakers should consider supporting hybrid renewable systems through incentives, subsidies, or financing schemes. This will accelerate adoption and contribute to energy access goals in underserved regions.

6 Further Research;Future studies should incorporate battery degradation modeling, real-time weather variability, and hybrid control strategies to enhance system realism. Comparative analysis with other renewable

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