THE RELIABILITY ASSESSMENT OF AN ISLANDED HYBRID PV-DIESEL-BATTERY SYSTEM FOR THE FACULTY OF ENGINEERING, UNIVERSITY OF BENIN

BY

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

FACULTY OF ENGINEERING

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A PROJECT SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENT

FOR THE AWARD OF BACHELOR OF ENGINEERING (BENG), UNIVERSITY OF BENIN, BENIN CITY.

SUPERVISOR: PROF. K. O. OGBEIDE

OCTOBER, 2025.

CERTIFICATION

This is to certify that this project work was carried out by IKIMI EHIGIE DANIEL with matriculation number ENG2002253, MICHEAL UCHENNA GODSWILL with matriculation number ENG2006267, BENEDICT YUNANA with matriculation number ENG2006278 and IBRAHIM EMIKE USMAN with matriculation number ENG2002245 in the department of Electrical and Electronics Engineering, University of Benin, Benin City, Edo State, Nigeria.

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(Project Supervisor)

____________________ __________________

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(H.O.D., Electrical and Electronics Engineering)

DEDICATION

We dedicate this work to our families, friends, and mentors, whose unwavering support, patience, and encourage have been instrumental in our journey.

We also extend our gratitude to our Supervisor, Prof. K. O. Ogbeide and all those who have inspired and guided us throughout this research. Their wisdom and dedication to knowledge have been a source of motivation.

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We extend our deepest gratitude to God Almighty for granting us the strength and perseverance to complete our journey at the University of Benin in pursuit of a Bachelor's degree in Electrical and Electronic Engineering. Through His grace, we successfully navigated this project despite the challenges posed by the condensed academic calendar and other obstacles.

Our sincere appreciation goes to our project supervisors, PROF. K. O. OGBEIDE, whose patience, guidance, and unwavering support were invaluable throughout this process.

We would like to express special thanks to our parents and guardians for their constant encouragement and unwavering support throughout our academic journey.

We are also immensely grateful to our friends and other group members who stood by us and provided assistance whenever we needed it—their kindness and support helped us overcome numerous challenges.

Lastly, a heartfelt appreciation goes to every member of the Electrical and Electronic Engineering graduating class of 2024/2025. The journey was far from easy, but together, we made it to the finish line.

Congratulations to us all!

ABSTARCT

The chronic unreliability of Nigeria's national power grid necessitates a dependency on costly and environmentally damaging diesel generators, particularly for critical institutions like universities. The literature validates Hybrid Renewable Energy Systems (HRES), specifically the Photovoltaic (PV)-Diesel-Battery configuration, as a technically superior and sustainable alternative for off-grid power. However, a granular, site-specific reliability assessment for the unique and energy-intensive load profile of a Nigerian engineering faculty represents a significant gap in existing research. This study addresses this gap by providing a bespoke techno-economic analysis and reliability evaluation for a standalone hybrid power system for the Faculty of Engineering at the University of Benin.

This research adopts a simulation-based methodology centered on the Hybrid Optimization Model for Multiple Energy Resources (HOMER) Pro software. The analysis is founded on a comprehensive on-site electrical load survey, which determined the faculty's detailed operational patterns and an annual energy demand of 737,686 kWh. This granular, real-world load profile, along with local solar irradiance and ambient temperature data for Benin City, was used to model, simulate, and optimize thousands of system configurations. The primary objective of the optimization was to identify the component sizing (PV array, battery bank, and diesel generator) that meets the faculty's load with the highest reliability at the lowest possible life-cycle cost.

The simulation results identified an optimal system configuration consisting of a 525 kW PV array, a 198 kWh Battery Energy Storage System (BESS), and an 85kW diesel generator relegated to a backup role. This system achieves 100% reliability with zero unmet load, a 100% renewable energy fraction, and a highly competitive Levelized Cost of Energy (LCOE) of ₦0.0548/kWh. The analysis confirms that this configuration completely displaces the need for diesel fuel, thereby

eliminating significant operational costs and preventing approximately 553 tonnes of CO_2 emissions annually. The findings conclusively demonstrate that a properly sized PV-Battery hybrid system is a technically reliable, economically superior, and environmentally sustainable solution to the faculty's energy challenges.

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NOMENCLATURE

AC: Alternating Current

BEDC: Benin Electricity Distribution Company

BESS: Battery Energy Storage System

CAPEX: Capital Expenditure

CO_2: Carbon Dioxide

CSV: Comma-Separated Values

DC: Direct Current

DG: Decentralized Generation

DoD: Depth of Discharge

ENS: Energy Not Supplied

GHI: Global Horizontal Irradiance

HOMER: Hybrid Optimization Model for Multiple Energy Resources

HRES: Hybrid Renewable Energy Systems

IEA: International Energy Agency

LCOE: Levelized Cost of Energy

LF: Load-Following

Li-ion: Lithium-Ion

LOLE: Loss of Load Expectation

LOLP: Loss of Load Probability

LPSP: Loss of Power Supply Probability

NOx: Nitrogen Oxides

NPC: Net Present Cost

NREL: National Renewable Energy Laboratory

O&M: Operational and Maintenance

PM2.5: Fine Particulate Matter

PV: Photovoltaic

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The relentless growth of the global population, coupled with rapid industrialization in developing economies, has precipitated an unprecedented demand for energy. This escalating demand presents a dual challenge for the international community: ensuring energy security while simultaneously mitigating the adverse effects of climate change driven by the combustion of fossil fuels (IEA, 2023). In response, a global paradigm shift is underway, moving away from conventional, carbon-intensive energy sources towards cleaner, sustainable, and renewable alternatives. This transition is not merely an environmental imperative but a crucial enabler of sustainable economic development, particularly for nations grappling with energy poverty and infrastructural deficits. Nigeria, despite being endowed with abundant conventional and renewable energy resources, exemplifies this paradox, facing a chronic and debilitating electricity crisis that has stalled its developmental aspirations for decades.

The Nigerian power sector has been persistently plagued by deep-seated issues, including inadequate generation capacity, a dilapidated transmission and distribution network, and systemic inefficiencies that result in a highly unreliable national grid (Sambo, 2009). The consequence is a sporadic and unpredictable power supply that falls profoundly short of the nation's needs, creating a significant impediment to industrial growth, commercial enterprise, and the effective functioning of essential public services. This energy deficit is acutely felt within the nation's tertiary education sector. Universities, as centers of research, innovation, and learning, are inherently energy-intensive environments. The functionality of modern pedagogical tools, scientific laboratories, computational research facilities, and digital libraries is contingent upon a stable and uninterrupted supply of high-quality electricity. The prevailing unreliable power situation frequently disrupts academic calendars, compromises sensitive research experiments, and diminishes the overall quality of education delivered to students (Adewale and Adepoju, 2017).

Faced with the failure of the public utility, many institutions, including the University of Benin, have been compelled to rely on self-generation to bridge the energy gap. The default solution has overwhelmingly been the deployment of diesel-fueled generators. While offering autonomy from the erratic national grid, this approach is fundamentally unsustainable. The operational expenditure is substantial, driven by the volatile and often escalating cost of diesel fuel, coupled with rigorous and expensive maintenance schedules. Furthermore, the environmental and social costs are severe; diesel generators are major sources of greenhouse gas emissions, including carbon dioxide (CO_2) and nitrogen oxides (NO_x), as well as other pollutants like particulate matter, which degrade local air quality. The attendant noise pollution is also a significant disruptor in an academic setting that requires tranquility for concentration and learning (Aliyu *et al*., 2018).

This unsustainable reality has catalyzed a growing interest in harnessing Nigeria's immense renewable energy potential, particularly its abundant solar resources. Located within a high solar insolation belt, the country is ideally positioned to leverage solar photovoltaic (PV) technology as a mainstream energy source. However, the inherent intermittency of solar power, dictated by the diurnal cycle and unpredictable weather patterns, poses a significant reliability challenge for its application as a standalone solution for critical loads. To surmount this obstacle, Hybrid Renewable Energy Systems (HRES) have emerged as a technically robust and increasingly viable solution. These systems intelligently combine two or more energy sources to capitalize on their respective strengths, thereby ensuring a more consistent and reliable power output than any single source could provide alone.

A particularly effective and widely adopted hybrid configuration for islanded applications is the PV-Diesel-Battery system. This architecture creates a synergistic relationship between its components to optimize for reliability, cost, and environmental performance. In this system, the solar PV array serves as the primary and cleanest source of energy, generating electricity throughout the daylight hours. A Battery Energy Storage System (BESS) is integrated to capture and store surplus solar energy, which can then be dispatched during periods of low or no solar input, such as on cloudy days or at night. The battery also plays a crucial role in enhancing power quality by stabilizing the system's voltage and frequency. The diesel generator is strategically relegated to a tertiary or backup role, programmed to operate only when the load demand exceeds the combined output of the PV array and the stored battery energy (Shaahid and El-Amin, 2009). This mode of operation drastically reduces the generator's runtime, leading to significant fuel savings, lower maintenance costs, and a substantial reduction in harmful emissions.

It is within this multifaceted context that the present study is situated. The Faculty of Engineering at the University of Benin is a critical hub for the training of the nation's future engineers and for conducting research that drives technological innovation. The faculty's reliance on a consistent and high-quality power supply for its specialized laboratories, workshops, and computational infrastructure cannot be overstated. By proposing an islanded PV-Diesel-Battery hybrid system, this study addresses the faculty's pressing need for a reliable, cost-effective, and environmentally responsible power solution. A rigorous and quantitative assessment of the reliability of such a system, tailored to the specific load profile of the faculty, is therefore the essential and logical first step toward its potential implementation.

1.2 Problem Statement

The Faculty of Engineering at the University of Benin is confronted with a persistent and critical operational challenge rooted in the profound inadequacy of the public electricity supply. The power delivered from the national grid via the Benin Electricity Distribution Company (BEDC) is characterized by chronic unreliability, manifesting as frequent, unscheduled outages, prolonged blackouts, and poor power quality with voltage and frequency fluctuations. This erratic energy supply constitutes a fundamental barrier to the faculty's core mission of providing high-caliber engineering education and conducting impactful scientific research. The direct consequences are severe, leading to constant disruptions of academic activities where laboratory experiments are prematurely terminated, wasting valuable materials and compromising learning outcomes. Furthermore, sensitive and often irreplaceable research equipment is placed at high risk of damage from power surges and abrupt shutdowns, thereby stifling the progress of postgraduate research and innovation.

In an attempt to mitigate this debilitating energy deficit, the faculty has resorted to an extensive reliance on diesel-powered generators as an alternative power source. However, this strategy is not a sustainable solution but rather a reactive measure laden with its own set of prohibitive challenges. The financial burden is immense, as the institution is exposed to the volatile and steadily rising cost of diesel fuel, alongside significant operational expenditures for the constant maintenance and repair of the generators. These diverted funds represent a substantial opportunity cost, consuming resources that could otherwise be invested in academic facilities, research grants, or technological upgrades. Beyond the economic strain, this over-reliance on fossil fuel combustion creates an environment that is incongruent with a place of learning, contributing to significant noise pollution that disrupts lectures and private study, and releasing harmful greenhouse gases and particulate matter that degrade the local air quality.

While the adoption of a hybrid PV-Diesel-Battery system presents a technologically advanced and environmentally superior alternative, a critical barrier prevents its implementation: the absence of a robust, quantitative analysis validating its reliability for the faculty's specific operational context. University administrators and financial stakeholders are understandably hesitant to commit the significant capital investment required for such a project without data-driven assurance that the system can dependably meet the unique, fluctuating, and critical load demands of the engineering laboratories, workshops, and offices. Therefore, the central problem this research addresses is the lack of a formal and specific reliability assessment for an islanded hybrid PV-Diesel-Battery power system designed and optimized for the energy consumption profile of the Faculty of Engineering, University of Benin. This knowledge gap creates uncertainty and impedes informed decision-making, leaving the faculty tethered to an unreliable and unsustainable power infrastructure.

1.3 Aim and Objectives of the Study

1.3.1 Aim of the Study

The aim of this project is to evaluate the reliability of a standalone hybrid system that integrates photovoltaic, diesel, and battery energy sources to provide a stable, continuous, and environmentally friendly power supply to the Faculty of Engineering at the University of Benin.

1.3.2 Objectives of the Study

To achieve this aim, the following objectives will be pursued:

i. To determine the detailed daily and seasonal electrical load profile of the Faculty of Engineering.

ii. To obtain and analyze solar irradiance and ambient temperature data relevant to the University of Benin's geographical location.

iii. To design and size the core components (PV array, battery bank, diesel generator) of a hybrid energy system capable of meeting the faculty's load demand.

iv. To model and simulate the performance of the designed hybrid system over a typical year using a specialized software HOMER Pro.

v. To evaluate the reliability of the system by quantifying key performance indices such as the Loss of Power Supply Probability (LPSP) and Energy Not Supplied (ENS).

1.4 Scope of the Study

This study is exclusively confined to the building complex of the Faculty of Engineering at the Ugbowo Campus of the University of Benin, Benin City. The electrical load data and subsequent system design will pertain solely to this defined area, and will not be extrapolated to the entire university campus. The technical scope of the investigation is strictly limited to the analysis of an islanded, or off-grid, hybrid power system. The specific architecture under consideration consists of a solar photovoltaic (PV) array, a battery energy storage system (BESS), and a backup diesel generator. Consequently, other potential renewable energy sources, alternative system configurations, or any form of interaction with the national grid, such as grid-tied or grid-supported systems, fall outside the purview of this work.

The methodology employed will be centered on computer-based modeling and simulation using industry-standard energy analysis software. This approach will allow for a dynamic, year-long performance analysis based on meteorological and load data. It is crucial to note that the scope of this project is therefore theoretical and analytical; it does not involve the physical procurement, installation, construction, or commissioning of any hardware components. The primary analytical focus is the quantitative assessment of the system's technical reliability, which will be evaluated using established engineering metrics like the Loss of Power Supply Probability (LPSP). While the simulation may yield economic data as a secondary output, a comprehensive financial investment analysis or a detailed Levelized Cost of Energy (LCOE) comparison is considered beyond the central objective of this specific study.

1.5 Significance of the Study

The successful completion of this research is poised to yield significant benefits for the University of Benin and contribute meaningfully to the broader energy discourse in Nigeria. Primarily, this study will provide the university's management and key stakeholders with a scientifically rigorous, data-driven basis for making an informed investment decision. By moving beyond anecdotal evidence and providing a quantitative assessment of the proposed system's ability to reliably meet the faculty's power demands, this work serves as a critical feasibility report that can unlock the necessary capital for a sustainable energy transition. Moreover, the detailed methodology, load profiling techniques, and system design parameters established in this study will serve as a valuable and scalable blueprint. This model can be readily adapted for implementation in other faculties within the university and can be replicated by other Nigerian tertiary institutions that are contending with similar debilitating power challenges.

Beyond its immediate institutional utility, this research holds considerable academic and environmental significance. It will make a tangible contribution to the body of scholarly literature on hybrid renewable energy systems, offering specific performance data and analysis relevant to the unique climatic conditions and operational realities of Southern Nigeria. This localized data is essential for refining system designs and improving the accuracy of future energy projects in the region. Furthermore, the study champions the cause of environmental sustainability within the academic community. By demonstrating a viable and reliable pathway to drastically reduce dependence on fossil-fuel-powered generators, the research promotes a reduction in the university's carbon footprint and noise pollution. It positions the Faculty of Engineering and, by extension, the University of Benin, as a forward-thinking institution committed not only to solving its immediate operational problems but also to embracing its role as a leader in environmental stewardship and the adoption of clean energy technologies.

CHAPTER TWO

LITERATURE REVIEW

2.1 The Nigerian Energy Crisis and the Case for Decentralized Generation

The persistent and multifaceted energy crisis in Nigeria represents one of the most significant and extensively documented impediments to its national development and economic aspirations. Scholarly literature, spanning several decades, consistently portrays a power sector in a state of chronic distress, fundamentally anchored to a centralized grid system that is demonstrably incapable of meeting the demands of a burgeoning population and an industrializing economy. The entire energy value chain, from generation through transmission to distribution, is fraught with deep-seated inefficiencies. Seminal studies by authors such as Adenikinju (2003) and Sambo (2009) have meticulously detailed these systemic frailties, which include insufficient and often unavailable generation capacity due to gas supply constraints to thermal plants, a fragile and radial transmission network susceptible to frequent collapses, and an obsolete distribution infrastructure plagued by high technical and non-technical losses. This systemic dysfunction culminates in frequent, unscheduled, and often prolonged power outages, a reality that has severely constrained national productivity and undermined the quality of life (Iwayemi, 2008). The economic consequences of this endemic power failure are staggering; studies have shown that the Nigerian economy forfeits billions of dollars in annual revenue, as industries are forced to operate far below their installed capacity, and the high cost of alternative power sources renders locally manufactured goods uncompetitive on the global market (Okafor, 2012).

In this vacuum of reliable public supply, a pervasive culture of self-generation has become entrenched across the nation, with businesses, institutions, and households overwhelmingly resorting to the use of diesel-fueled generators. This reactive strategy, however, has evolved into an unsustainable and economically inefficient parallel power system. Aliyu *et al*. (2018) provide a compelling analysis of the detrimental effects of this dependence, highlighting the exorbitant and volatile operational expenditures driven by the global price of petroleum products, coupled with the intensive maintenance cycles required by the generators. This financial burden diverts enormous capital away from core productive investments and into operational stopgaps. Furthermore, the environmental and social costs are profound; the unabated combustion of diesel fuel releases substantial quantities of greenhouse gases, primarily carbon dioxide (CO2), and a host of harmful local air pollutants such as nitrogen oxides (NOx) and fine particulate matter (PM2.5), which have been linked to significant public health crises, particularly respiratory illnesses in urban centers (Adewale and Adepoju, 2017). The incessant acoustic pollution from these generators further degrades the living and working environment, a particularly acute problem for institutions like universities that require a serene atmosphere for learning and research.

This confluence of a failed centralized grid and the unsustainable nature of isolated diesel generation creates a compelling and urgent case for a fundamental paradigm shift towards decentralized generation (DG). As defined and explored by Ackermann *et al*. (2001), DG refers to the deployment of smaller, modular power generation technologies at or near the point of consumption. This approach directly counters the weaknesses of the centralized model by eliminating reliance on the fragile long-distance transmission network, thereby drastically reducing energy losses and enhancing supply reliability. By empowering institutions like the University of Benin to take control of their energy destiny, DG, particularly when integrated with renewable sources, offers a clear pathway to achieving energy security, operational stability, and environmental sustainability. It represents a more resilient, efficient, and modern energy architecture suited to the challenges and opportunities of the 21st century.

2.2 Concept of Hybrid Renewable Energy Systems (HRES)

The conceptual framework of a Hybrid Renewable Energy System (HRES) arises directly from the need to overcome the intrinsic limitations of standalone power generation technologies, particularly the intermittency associated with renewable energy sources. In the academic literature, an HRES is broadly defined as a power generation system that intelligently integrates two or more energy conversion technologies, with the requisite that at least one of the sources is renewable, to supply a specific electrical load in a reliable and efficient manner (Bhandari *et al*., 2014). The fundamental principle underpinning the HRES concept is that of synergy and complementarity; by combining different energy sources, the weaknesses of one component can be mitigated by the strengths of another. This integration results in a composite system that offers superior technical performance, economic viability, and environmental benefits compared to any of its constituent parts operating in isolation. For instance, the predictable intermittency of a solar photovoltaic (PV) system, which only generates power during daylight hours, can be effectively counteracted by integrating it with a dispatchable source like a diesel generator or an energy storage medium like a battery bank, thus ensuring a continuous and stable supply of power (Chedid *et al*., 1998).

The strength of an HRES lies in its operational logic, which is designed to optimize the dispatch of available energy resources based on the load demand, resource availability, and economic constraints. Different configurations have been extensively studied and deployed globally, each tailored to specific geographical and load characteristics. Common configurations reviewed in the literature include PV-Wind hybrids, which exploit the often-complementary nature of solar and wind resources, and PV-hydro systems for locations with suitable topography. However, for off-grid applications in regions with high solar insolation but without other consistent renewable resources, the PV-Diesel-Battery configuration has emerged as a particularly robust and widely adopted solution (Nema *et al*., 2010). This specific architecture provides a multi-layered approach to reliability. The PV array serves as the primary and most economical energy producer, generating clean electricity at a near-zero marginal cost whenever sunlight is available.

The Battery Energy Storage System (BESS) is the pivotal component that enables high renewable penetration and ensures system autonomy. Its role is multifaceted: it absorbs and stores surplus energy generated by the PV array during periods of low demand or peak solar irradiance, and subsequently discharges this stored energy to meet the load during the night or on overcast days. This function, known as energy shifting, is critical for decoupling power generation from immediate consumption (Divya and Ostergaard, 2009). Furthermore, the battery bank provides crucial ancillary services by stabilizing the system's voltage and frequency, thereby improving the overall quality and reliability of the power supplied. Finally, the diesel generator is strategically relegated to a tertiary, backup role. In an optimized HRES, the generator is programmed to operate only during extended periods of low solar input when the battery state of charge is depleted, or to meet rare, exceptionally high peak loads. This operational strategy, as validated by the results of this present study, drastically minimizes the generator's runtime, which in turn leads to profound reductions in fuel consumption, maintenance requirements, noise pollution, and harmful emissions (Shaahid and El-Amin, 2009). The HRES concept, therefore, represents a sophisticated and effective engineering solution, transforming intermittent renewable resources into a firm, reliable, and sustainable power supply.

2.2.1 The Evolving Role of Diesel Generators in HRES

Diesel generator sets have, for much of the past century, been the undisputed workhorse for off-grid and backup power generation, particularly across the developing world. Their historical dominance is rooted in a combination of compelling technical attributes: high power density, technological maturity, a well-established global supply chain, and, most importantly, their fully dispatchable nature, allowing for on-demand power generation independent of external conditions (Bhattacharyya, 2013). In contexts like Nigeria, where the public grid is unreliable, the diesel generator became the default, almost ubiquitous, solution for ensuring operational continuity in critical institutions. In this traditional standalone application, the generator functions as the primary baseload power source, singularly responsible for meeting the entire load profile and consequently operating for protracted, often continuous, periods. However, the integration of diesel generators into the sophisticated framework of a Hybrid Renewable Energy System (HRES) instigates a fundamental paradigm shift in their operational philosophy. The generator is strategically repositioned within the system's dispatch hierarchy, evolving from its role as a primary energy provider to that of a crucial, yet subordinate, component dedicated to guaranteeing system reliability.

This transformation is orchestrated by the intelligent dispatch controller that forms the brain of the hybrid system. This controller manages the flow of energy based on a "merit order" that prioritizes resources according to their marginal cost of production. Solar energy, with a marginal cost of zero, is invariably at the top of this hierarchy, followed by the stored energy in the battery. The diesel generator, with its high marginal cost dictated by fuel consumption, is placed at the bottom of the dispatch order (Barakat *et al*., 1999). It is only called into service when the primary and secondary resources (PV and battery) are exhausted or collectively insufficient to meet the instantaneous load. This operational logic is not merely a matter of preference but is also rooted in the technical performance of diesel engines. Generators operate with optimal fuel efficiency when loaded to between 75% and 100% of their rated capacity. Operating at low loads (below 40%) is extremely inefficient and can lead to engine damage from conditions like "wet stacking," where unburnt fuel and soot accumulate in the exhaust system (Celikel, 2011). The HRES controller mitigates this by ensuring that when the generator does run, it is to meet a substantial load, thereby operating within its high-efficiency band.

The implications of this evolved role are profound and multifaceted. The most evident benefit, extensively validated in academic literature, is a drastic reduction in fuel consumption, which directly translates into significant lifelong operational cost savings and shields the user from the unpredictable volatility of diesel prices (Kaldellis *et al*., 2010). This curtailed runtime also has a direct and positive impact on the generator's health and longevity; since maintenance schedules are predominantly based on operating hours, a generator in an HRES requires far less frequent servicing, leading to reduced O&M costs and an extended operational lifespan. This optimized role also influences the initial system design, as the generator no longer needs to be sized to meet the absolute peak load of the facility. Instead, it can be sized smaller to work in concert with the battery and PV array to meet peaks, potentially reducing the initial capital outlay. Consequently, the modern role of the diesel generator in a hybrid system is that of a strategic enabler of reliability a dispatchable asset that provides firm capacity and black-start capability, guaranteeing 100% power availability while allowing the renewable components to deliver the vast majority of the energy, thereby maximizing the system's overall economic and environmental performance.

2.2.2 Methodology for HRES Design and Optimization

The transition from a conceptual hybrid system design to a feasible and implementable project is critically dependent on a rigorous process of techno-economic sizing and analysis. The performance, reliability, and financial viability of a Hybrid Renewable Energy System (HRES) are not merely determined by the selection of its components, but are intrinsically linked to the optimal sizing of each component in relation to the specific load demand and available energy resources (Connolly *et al*., 2010). This optimization process is fundamentally an exercise in navigating the inherent trade-off between minimizing the life-cycle cost of the system and maximizing its technical performance, particularly its reliability. An undersized system, while having a lower initial capital cost, will likely fail to meet the load demand reliably, leading to frequent power outages or an over-reliance on the costly diesel generator. Conversely, an oversized system may offer near-perfect reliability but at a prohibitively high capital expenditure, rendering the project economically unviable (Fadaeenejad *et al*., 2014). Techno-economic optimization, therefore, is the formal, data-driven methodology used to identify the system configuration that achieves the desired level of reliability at the lowest possible long-term cost.

At the core of this optimization process is the objective to minimize the system's total Net Present Cost (NPC). The NPC is a comprehensive financial metric that represents the total life-cycle cost of the system, encompassing all expenditures incurred throughout its operational lifetime, with all future costs discounted back to their present-day value to account for the time value of money (Short *et al*., 1995). It is a holistic measure that includes the initial capital expenditure (CAPEX) for all components, all future component replacement costs, and all operational and maintenance (O&M) costs, including fuel for the diesel generator. By consolidating all costs into a single value, the NPC provides a robust and standardized basis for comparing the long-term financial performance of thousands of different potential system configurations. From this, another crucial metric is derived: the Levelized Cost of Energy (LCOE). The LCOE is defined as the average cost per unit of electricity (/kWh) generated by the system over its entire life. It is calculated by dividing the total Net Present Cost by the total amount of energy delivered to the load over the project's lifetime. As established in the literature, the LCOE is an invaluable metric for benchmarking the cost-effectiveness of an off-grid hybrid system against alternatives, such as the cost of grid electricity or, more pertinently in this context, the cost of diesel-only generation (Rehman and Al-Hadhrami, 2010).

This complex optimization is carried out using sophisticated simulation models that perform an hour-by-hour energy balance over a full year (8,760 hours). These models process a range of inputs, including time-series data for the electrical load and solar resources, along with the technical and economic parameters of each component (e.g., efficiency, lifetime, cost). The simulation engine then explores a vast "search space" of possible component sizes, evaluating each potential combination against a primary constraint: system reliability. This constraint is typically defined as a maximum acceptable Loss of Load Probability (LOLP) or a minimum level of energy supply continuity (Ma *et al*., 2017). The model discards all configurations that fail to meet this reliability threshold. From the remaining pool of technically feasible solutions, the software identifies and ranks them according to their NPC and LCOE. This rigorous, iterative process ensures that the final recommended design is not only technically capable of meeting the load reliably but is also the most economically optimal solution over the long term, thereby providing a solid foundation for investment decisions.

2.3 Solar Photovoltaic (PV) Technology

Solar Photovoltaic (PV) technology represents the cornerstone of the proposed hybrid system and is a central pillar in the global transition towards sustainable energy. The fundamental principle of its operation is the photovoltaic effect, a phenomenon in solid-state physics where semiconductor materials, typically silicon, directly convert solar radiation (photons) into direct current (DC) electricity (Duffie and Beckman, 2013). The basic unit of this technology is the solar cell, with multiple cells interconnected to form a solar module or panel, which is the commercially available product. For larger power requirements, these modules are further configured into extensive solar arrays, allowing the technology to be exceptionally modular and scalable, capable of powering applications from small-scale residential systems to utility-scale power plants. The global adoption of PV technology has accelerated dramatically over the past two decades, driven by significant advancements in manufacturing, resulting in a continuous and steep decline in costs, a trend often referred to as Swanson's Law, alongside steady improvements in conversion efficiency (Goetzberger *et al*., 2003).

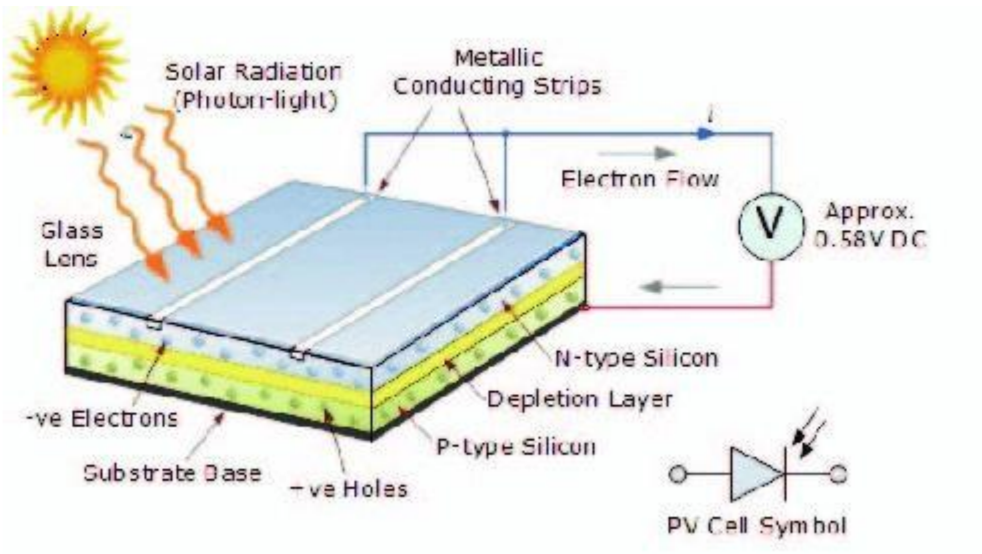

Figure 2.1 - Basic diagram of Photovoltaic solar cell

The applicability and potential of solar PV technology in Nigeria are immense, a fact strongly supported by the country's geographical location within the world's high solar radiation belt. Extensive studies have been conducted to quantify this resource, consistently showing that Nigeria receives an abundant amount of solar energy year-round. The national average for daily solar insolation ranges between 4.0 kWh/m² in the southern coastal regions to as high as 6.5 kWh/m² in the semi-arid northern frontier (Okoro and Madueme, 2004). For Benin City, the specific location of this study, the annual average global horizontal irradiance is approximately 4.9 kWh/m²/day, as confirmed by NASA meteorological data and corroborated by local research (Ajayi *et al*., 2014).

This vast, clean, and inexhaustible energy resource is largely untapped and presents a direct and viable alternative to the nation's over-reliance on fossil fuels.

Despite its compelling advantages and vast potential, the primary technical challenge of solar PV technology is its inherent intermittency and variability. The output of a PV array is not constant but is contingent upon several dynamic factors. The most significant of these is the predictable diurnal cycle, meaning that power generation is restricted to daylight hours and ceases entirely at night. Additionally, the power output is subject to unpredictable, stochastic fluctuations caused by changing meteorological conditions. The passage of clouds, seasonal haze such as that experienced during the Harmattan period, and the accumulation of dust on panel surfaces can all cause rapid and significant reductions in generation (Mekhilef *et al*., 2012). Furthermore, the efficiency of PV modules is temperature-dependent, with performance typically degrading as ambient temperatures rise, a pertinent issue in Nigeria's tropical climate. This fundamental characteristic of intermittency renders a standalone PV system inherently unreliable for powering critical loads, such as those found in an engineering faculty, which demand a consistent and uninterrupted supply of electricity 24 hours a day. Therefore, to harness Nigeria's solar potential for such applications, the PV system must be integrated into a hybrid configuration that incorporates components capable of mitigating this variability.

2.4 Battery Energy Storage Systems (BESS) in Off-Grid Application

Within the architecture of a modern Hybrid Renewable Energy System, the Battery Energy Storage System (BESS) transcends the role of a mere accessory to become the central enabling technology that guarantees reliability and unlocks the full potential of renewable sources. While photovoltaic panels are the primary engines of energy generation, the BESS is the critical component that provides the firmness, dispatchability, and stability required to transform their intermittent output into a consistent, 24/7 power supply suitable for critical loads (Luo *et al*., 2015). The integration of robust energy storage is arguably the most important factor in achieving high levels of system autonomy and minimizing reliance on fossil-fueled backup generation. Its function is far more sophisticated than simply storing and releasing energy; it acts as a dynamic buffer and a power quality conditioner, performing several distinct roles simultaneously to ensure the seamless operation of the entire off-grid system.

The primary and most widely understood function of the BESS in a PV-hybrid system is that of energy time-shifting. It effectively decouples the timing of electricity generation from the timing of its consumption. The BESS absorbs and stores the surplus, low-cost solar energy generated during peak sunlight hours when supply often exceeds demand, and then strategically discharges this energy to meet the electrical load during the evening and night-time hours, or during periods of low solar insolation due to cloud cover (Divya and Østergaard, 2009). This function is paramount as it directly displaces the energy that would otherwise need to be supplied by the diesel generator, thus maximizing the system's renewable fraction and generating significant fuel savings. Beyond this, the BESS is instrumental in ensuring power quality and system stability. With its ability to respond to electrical signals in milliseconds, a BESS can instantly inject or absorb power to smooth out the rapid and unpredictable fluctuations in PV generation, thereby maintaining a stable voltage and frequency on the system's AC bus, a task that a mechanically-driven, slow-to-start diesel generator cannot perform effectively (Rocabert *et al*., 2012). This capability is crucial for protecting sensitive electronic equipment typically found in an engineering faculty.

The choice of battery technology is a critical design consideration, with the literature extensively comparing traditional and modern solutions. For many years, deep-cycle lead-acid batteries were the standard for off-grid applications due to their mature technology and lower initial capital cost. However, they are limited by a lower depth of discharge (DoD), typically around 50%, a shorter cycle life, and lower round-trip efficiency (Zarrabeitia *et al.*, 2017). More recently, Lithium-Ion (Li-ion) batteries have become the dominant technology for HRES applications, a trend driven by a dramatic and continuous reduction in their manufacturing costs. As noted by Nykvist and Nilsson (2015), the advantages of Li-ion technology are substantial: they offer a much higher energy density, a longer cycle life, and superior performance characteristics, including a high round-trip efficiency (often exceeding 90%) and the ability to undergo deep discharges (80-90% DoD) without significant degradation. These superior technical parameters, which were adopted in the methodology of this study, allow for a more compact and efficient storage system, ultimately enabling a higher penetration of renewable energy. By providing a substantial and readily dispatchable reserve of stored energy, the BESS permits the installation of a much larger PV array relative to the load, ensuring that the system can operate reliably on clean energy for the vast majority of the time, further marginalizing the role of the diesel generator.

2.5 The Use of HOMER Pro Software in Hybrid System Design

Within the field of hybrid renewable energy systems, the Hybrid Optimization Model for Multiple Energy Resources (HOMER) Pro has emerged as the global de facto standard for both academic research and commercial microgrid design (Sinha and Chandel, 2014). Originally developed and disseminated by the United States National Renewable Energy Laboratory (NREL), HOMER Pro's credibility is built upon its powerful simulation capabilities and its extensive, successful application in thousands of studies and real-world projects. Its widespread validation in peer-reviewed literature makes its selection not just a matter of convenience, but a methodologically sound choice that aligns with established best practices in the energy systems analysis community.

The software provides a unified platform for modeling complex energy systems, evaluating their technical performance, and determining their economic viability with a high degree of granularity. The core functionality of HOMER Pro is built upon a sophisticated, time-step simulation engine. This engine performs a detailed energy balance calculation for every hour, or even every minute, over a full year totaling 8,760 or more discrete intervals. For each interval, the software meticulously calculates the electrical demand of the load and determines how that load can be met by the various components of the hybrid system, accounting for the available solar radiation, the battery's state of charge, and the operational status of the generator (Lambert *et al*., 2006). Its second, and perhaps most critical, function is optimization. Rather than analyzing a single, pre-defined system, HOMER simulates hundreds or thousands of different system configurations by systematically varying the sizes of the components within a user-defined search space. After simulating each configuration, the software calculates its life-cycle Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), and then ranks all technically feasible systems, allowing the user to identify the one that meets all constraints at the lowest possible cost. Furthermore, HOMER Pro is equipped with a powerful sensitivity analysis module, which allows researchers to assess the robustness of their results against uncertainties in key variables, such as future fuel prices or variations in solar resource availability (Akella and Sharma, 2007).

The utility and reliability of HOMER Pro are best evidenced by its ubiquitous presence in HRES literature. Numerous studies focused on the Nigerian context have employed the software to validate the feasibility of hybrid systems. For example, a comprehensive study by Olatomiwa *et al*. (2016) utilized HOMER to assess PV-diesel-battery configurations for six different remote communities across Nigeria, concluding in each case that the hybrid approach offered a far superior economic and environmental performance compared to standalone diesel generation.

Similar research has been conducted for institutional loads that mirror the context of this study. Al-Sharafi *et al*. (2017), for instance, applied HOMER to design an optimized hybrid system for a university campus, successfully demonstrating the tool's capacity to model complex, daytime-dominant load profiles and quantify significant potential savings. The software's detailed outputs on reliability metrics, such as Unmet Load and Loss of Load Probability (LOLP), have also made it an indispensable tool for studies where power supply continuity is the primary concern (Fadaeenejad *et al*., 2014). The consistent and successful application of HOMER Pro in the literature for a vast range of contexts provides an unequivocal validation of its use as the analytical engine for this present study.

2.6 Research Gap

The comprehensive review of the existing literature presented in this chapter provides a robust foundation for the current study. The body of scholarly work unequivocally establishes several key points. First, Nigeria's centralized power infrastructure is chronically unreliable, and the widespread practice of relying on standalone diesel generators is an economically burdensome and environmentally detrimental strategy. Second, Hybrid Renewable Energy Systems (HRES), and specifically the PV-Diesel-Battery configuration, have been extensively validated as a technically superior, economically efficient, and sustainable alternative for off-grid power generation. The literature clearly delineates the synergistic roles of the system components: the solar PV array as the primary clean energy source, the Battery Energy Storage System (BESS) as the critical enabler of reliability and high renewable penetration, and the diesel generator in its evolved role as a strategic backup. Furthermore, it is established that the design of such complex systems is optimally achieved through rigorous techno-economic analysis, for which specialized software like HOMER Pro has become the undisputed academic and industry standard.

Despite this extensive body of knowledge on the general feasibility and design principles of hybrid systems, a critical and specific gap persists in the context of Nigerian tertiary institutions. While previous research, such as the work by Olatomiwa *et al*. (2016), has valuably explored HRES applications for rural residential communities in Nigeria, there is a conspicuous absence of a granular, site-specific reliability assessment for a system designed to meet the unique and demanding load profile of a large, energy-intensive academic facility like a Faculty of Engineering. The energy consumption pattern of such a faculty, characterized by high daytime loads from laboratories, workshops, and computational equipment, is fundamentally different from the evening-peaked load profiles of residential communities. Consequently, the optimal system architecture, component sizing, and resultant reliability performance cannot be reliably extrapolated from existing studies.

This present study is therefore precisely formulated to address this identified gap. It moves beyond generalized feasibility analyses to conduct a bespoke, data-driven investigation using a meticulously compiled, real-world load profile from the Faculty of Engineering at the University of Benin. By focusing explicitly on the quantitative assessment of system reliability through metrics such as the Loss of Load Probability (LOLP), this research provides the rigorous performance validation that is essential for justifying significant capital investment. In doing so, this study aims to contribute valuable, actionable, and contextually specific knowledge that is currently absent in the literature. It will provide a critical engineering and economic blueprint that can guide the sustainable energy transition not only for the University of Benin but for other tertiary institutions across Nigeria facing similar energy challenges.

CHAPTER THREE

METHODOLOGY

3.1 Research Design

The research adopts a simulation-based design approach using HOMER Pro software to model and analyze a standalone hybrid energy system. The system integrates photovoltaic (PV), diesel generator, and battery storage components to provide a reliable, cost-effective, and environmentally sustainable power supply for the Faculty of Engineering, University of Benin.

3.2 Load Data Preparation and Processing

HOMER Pro (Hybrid Optimization Model for Multiple Energy Resources) is a microgrid simulation tool developed by the U.S. National Renewable Energy Laboratory (NREL). It enables users to design hybrid energy systems by optimizing component sizes based on cost, reliability, and environmental impact. HOMER performs energy balance calculations for every hour of the year (8,760 hours) and determines the most economical system configuration that meets the energy demand.

Before simulation, the raw energy-use data for the Faculty of Engineering were compiled from on-site measurements, departmental records, and equipment power ratings. The data were presented in a document titled *"Updated Load Survey of Faculty of Engineering"*, which contained the connected and operating wattages of appliances across lecture rooms, laboratories, offices, workshops, and administrative units.

3.2.1 Data Compilation

Each department and unit within the faculty was surveyed to identify all electrical appliances in use. The nameplate ratings (in watts) of lighting fixtures, fans, air conditioners, computers, laboratory instruments, and other electrical loads were recorded. In addition, their usage duration (hours/day) and duty cycles were estimated through interviews with staff and direct observation. For each load point, two values were computed:

i. Connected Load (W**):** The total rated capacity of all devices installed.

ii. Running Load (W): The actual power consumed under normal operating conditions, derived from the connected load multiplied by a diversity factor or utilization factor**.**

This process produced a detailed breakdown of energy use for all subunits of the Faculty of Engineering.

3.2.2 Aggregation and Estimation of Total Demand

The individual departmental consumption values were summed to determine the aggregate running load of the entire faculty. From the survey results:

i. Total connected load**:** approximately *305 kW*

ii. Total running load: approximately *202 kW*

The average daily energy consumption was then estimated using:

$$E_{daily} = P_{avg} \times 24 hours$$

This yielded about 2020kWh/day. This represents the baseline demand required to sustain normal academic and laboratory operations.

3.2.3 Development of Hourly Load Profile

Since HOMER Pro requires an 8,760-hour (hour-by-hour) annual load profile, the aggregated data were converted into a time-series format using spreadsheet modeling. The following steps were performed:

i. Daily Load Curve Generation: The daily variation pattern of power use was created, showing higher demand between 8:00 a.m. and 6:00 p.m**.** (peak working hours) and reduced demand at night.

ii. Weekday–Weekend Adjustment: The weekday load profile was scaled by approximately 60–65 % for weekends to reflect reduced academic activity.
iii. Annual Expansion: The representative daily profiles were repeated for 365 days, producing an 8,760-hour dataset.
iv. Data Validation: The total annual energy from the time series (737,686 kWh/year) matched the expected yearly consumption computed from the field data, confirming accuracy.

3.2.4 Conversion to HOMER-Compatible Format

The hourly data were exported to a comma-separated values (CSV) file named:

faculty_engineering_load_8760.csv

The file contained the following columns:

i. Date-time (hourly timestamps for one year)
ii. Hour of year (1–8760)
iii. Load kW (hourly load in kilowatts)

This formatted dataset was imported into HOMER Pro as the *Primary Load Input*, forming the foundation for subsequent hybrid system simulation and optimization.

3.3 Data Collection

The data used for the modeling and simulation of the hybrid PV–Diesel–Battery system were obtained through a combination of on-site measurements, load survey, and secondary sources. The information was organized and entered into HOMER Pro to provide all the technical and economic inputs required for accurate optimization.

3.3.1 Electrical Load Data

A comprehensive load survey was conducted within the Faculty of Engineering, University of Benin, to determine the electrical demand of lecture rooms, laboratories, offices, workshops, and auxiliary facilities. The power ratings and usage durations of all appliances were recorded and converted into equivalent energy. From the compiled data, the average running load was about 2020kW, with a peak demand of approximately 196 kW and an annual energy requirement of approximately 737,686 kWh. These values were used to generate an hourly (8,760-hour) load profile representing one full year of operation. The profile was imported into HOMER Pro as a Primary Load file (faculty_engineering_load_8760.csv), and it reflects higher daytime activity typical of an academic environment and lower consumption at night and during weekends. Figure 3.1 shows the electrical load data.

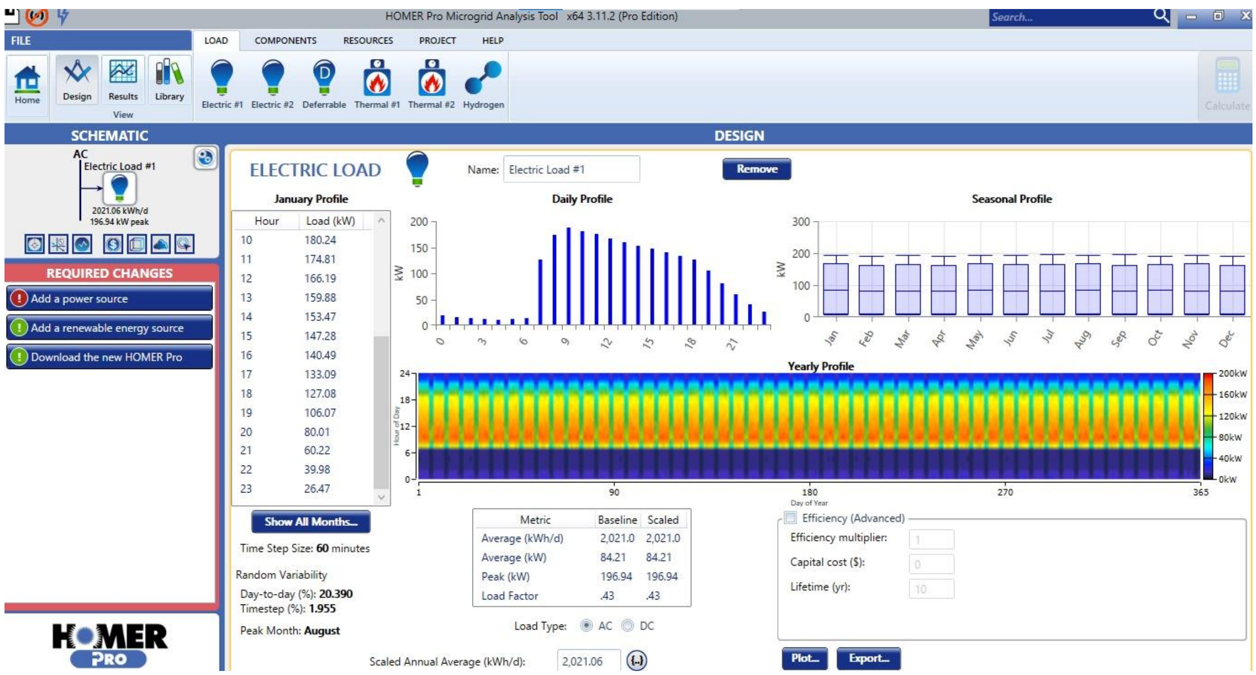

Figure 3.2 - Electrical Load Data

3.3.2 Solar Resource Data

The solar resource for Benin City (Latitude 6.33° N, Longitude 5.62° E) was obtained from NASA Surface Meteorology and Solar Energy data integrated in HOMER Pro. The mean global horizontal irradiance (GHI) ranges between 4.1 and 5.7 kWh/m²/day, with an annual average of about 4.9kWh/m²/day. The corresponding monthly average ambient temperatures, derived from the same source, vary from 25 °C to 29 °C. These data sets define the solar potential available to the photovoltaic subsystem and were entered manually where necessary to ensure completeness.

Table 3.1 - Monthly GHI Reading

MONTH	**GHI (kWh/m²/day)**	**AVG TEMP (°C)**
JAN	5.2	28
FEB	5.6	29
MAR	5.7	29
APR	5.5	28
MAY	5.0	27
JUN	4.5	26
JUL	4.3	25
AUG	4.1	25
SEPT	4.5	26
OCT	5.0	27
NOV	5.3	28
DEC	5.4	28

Figure 3.2 shows the temperature resource data and figure 3.3 shows the solar GHI data.

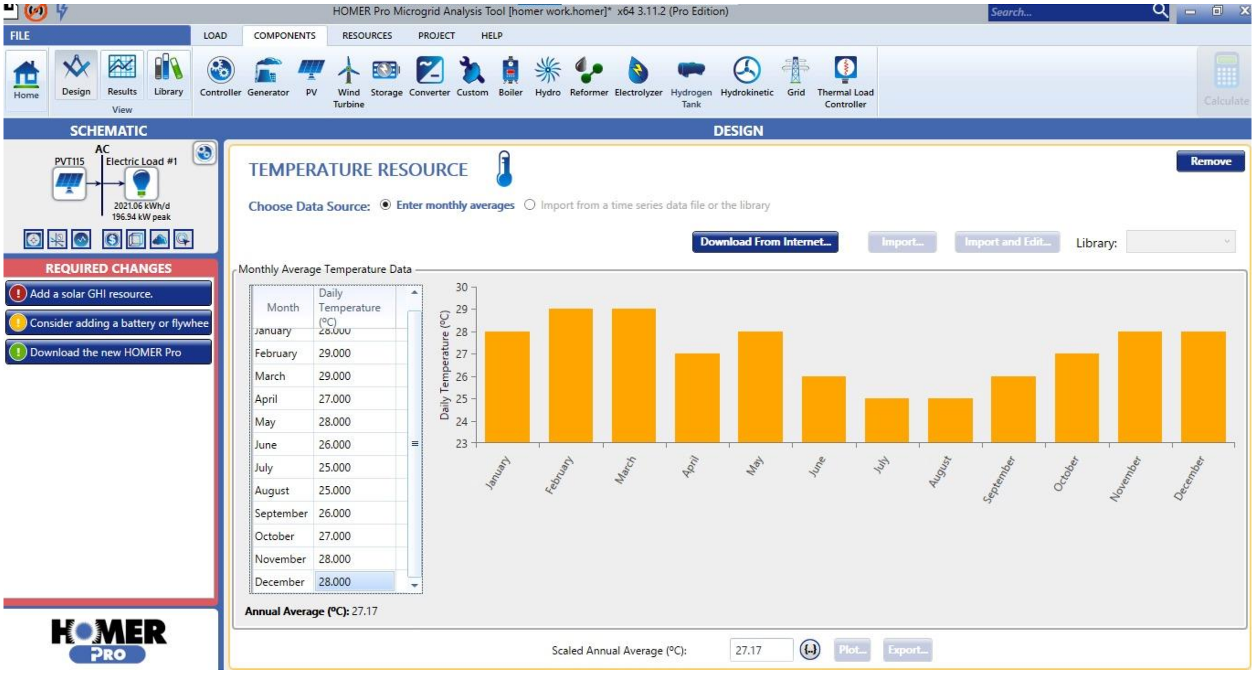

Figure 3.2 - Temperature Resource Data

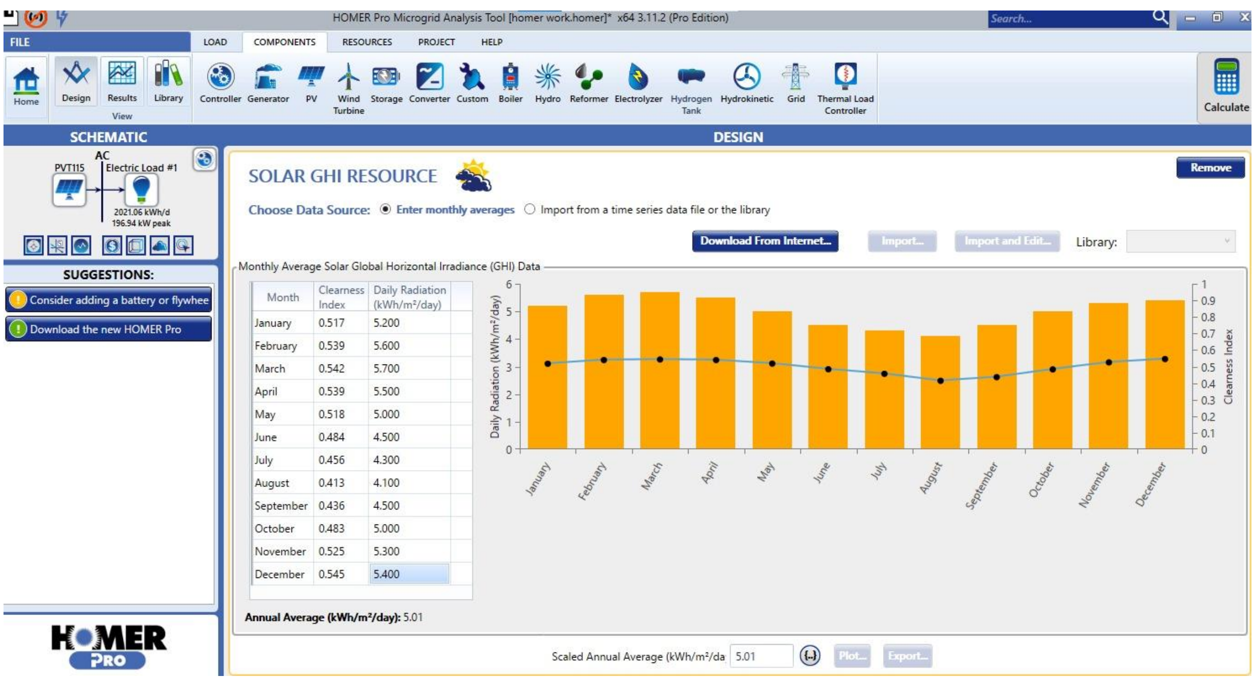

Figure 3.4 - Solar GHI Resource Data

3.3.3 Component and Cost Data

The techno-economic characteristics of each system component were obtained from manufacturers' catalogues, market surveys, and relevant literature. These parameters were entered into HOMER Pro to guide the optimization process.

Table 3.2 - Component and Cost Data Parameters

COMPONENT	CAPACITY RANGE	LIFETIME	EFFICIENCY
Photovoltaic Array	200 – 600 kW	25 yrs	Derating factor = 85 %
Diesel Generator	200 – 400 kW	15,000 operating hours	Specific fuel consumption = 0.28 L/kWh
Battery Bank	500 – 6,000 kWh	10 yrs	DoD = 80 %, Efficiency = 90 %
Converter / Inverter	300 – 400 kW	15 yrs	Inverter eff. = 95 %, Rectifier eff. = 90 %

A diesel fuel price of ₦1,200 per litre (local average in 2025) was adopted with an annual escalation rate of 2 %. The project lifetime and discount rate were taken as 20 years and 8 %, respectively, consistent with typical engineering-economic analyses.

3.4 System Modeling and Simulation Procedure

The modeling and simulation process was carried out using HOMER Pro, which enables detailed techno-economic analysis of hybrid renewable energy systems. The procedure involved defining the system structure, specifying component characteristics, and performing an optimization run to determine the most economical and reliable configuration capable of meeting the Faculty of Engineering's electrical demand.

3.4.1 Model Description

The proposed system is a stand-alone PV–Diesel–Battery hybrid designed to supply continuous power to the Faculty of Engineering complex. It consists of:

i. a **photovoltaic (PV) array** that converts solar radiation into electricity,
ii. a **diesel generator** to provide backup supply during low-solar or peak-demand periods,
iii. a **battery storage unit** to store excess PV energy and discharge it when needed, and
iv. a **converter (inverter/rectifier)** that links the DC and AC buses.

HOMER Pro models the power balance for each of the 8,760 hours in a year, ensuring that total generation (from PV, battery, and generator) always equals the electrical demand plus system losses.

3.4.2 Model Development in HOMER Pro

The simulation was developed through the following steps:

i. **Project Setup:**

   A new project titled *"Faculty of Engineering Hybrid Power System"* was created. The geographic coordinates of Benin City, Nigeria (6.33° N, 5.62° E) were entered to enable access to NASA solar-irradiance data.

ii. **Load Definition:**

   The hourly electrical demand profile (faculty_engineering_load_8760.csv) was imported as the *Primary Load*. HOMER automatically displayed the daily and seasonal variations corresponding to the faculty's operational pattern.

iii. **Resource Specification:**

Monthly averages of solar global horizontal irradiance (GHI) and ambient temperature were entered as shown in Table 3.1. These values define the solar energy potential available to the PV subsystem.

iv. **Component Addition and Parameter Entry:**

The major components PV array, diesel generator, battery storage, and converter were inserted into the system schematic. Each component's cost, efficiency, and lifetime data were entered based on Table 3.2.

- The PV array and battery were connected to the DC bus,
- the generator and load were connected to the AC bus, and
- the converter linked both buses, permitting bidirectional power flow.

v. **Economic Settings:**

Project life = 20 years; discount rate = 8 %; diesel price = ₦1,200 per L with 2 % annual escalation.

vi. **Dispatch and Control Strategy:**

The Load-Following (LF) dispatch strategy was selected. Under this scheme, the generator operates only when the renewable sources and battery cannot meet the load, thereby minimizing fuel consumption and emissions.

vii. **Optimization and Sensitivity Analysis:**

HOMER was instructed to evaluate different component sizes:

- PV = 200 – 600 kW,
- Battery = 500 – 6,000 kWh,
- Generator = 200 – 400 kW,

- Converter = 300 – 400 kW.

The software automatically simulated all feasible combinations and ranked them according to the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE).

Sensitivity analyses were later conducted on diesel-price and solar-radiation variations to evaluate system robustness.

3.4.3 Model Validation and Output

After the whole data has been placed into the Homer Pro software, various checks was done to see if everything was in place. We had to make sure that the schematic panel was set according to standard. We had to ensure that the DC bus (PV + Battery) connects through it to the AC bus (Generator + Load). Figure 3.4 shows a diagram of the software processing the information.

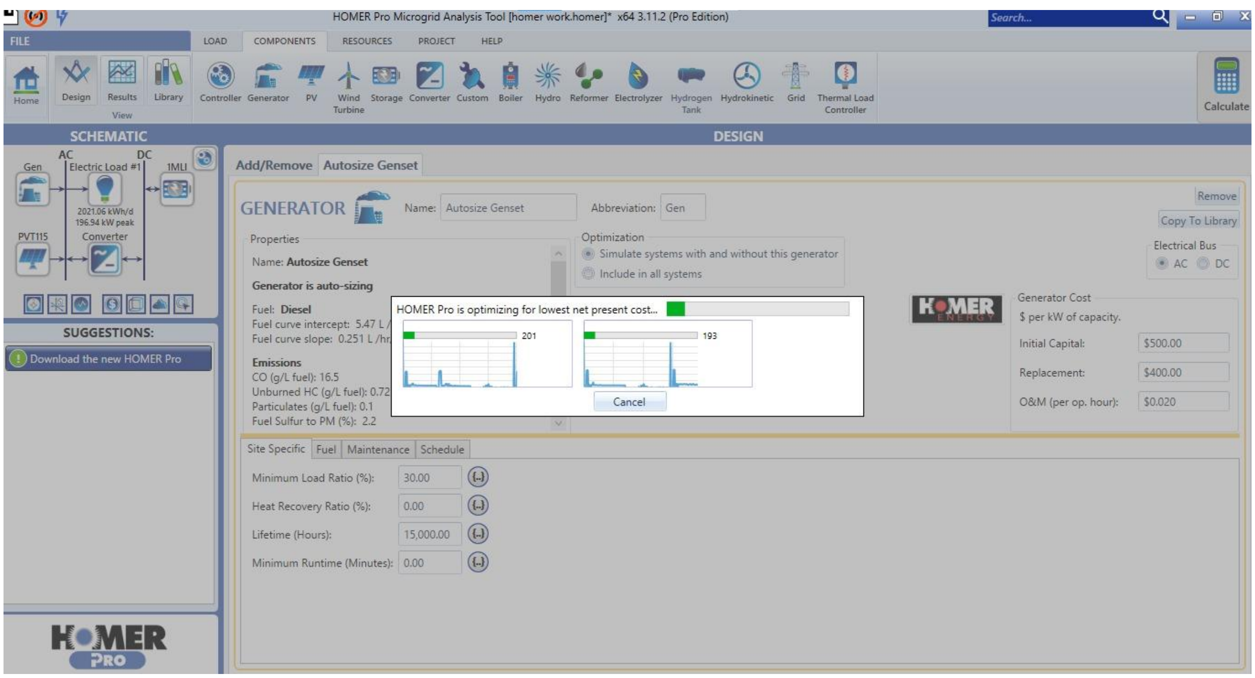

Figure 3.5 - HOMER Pro Processing

After successful execution, HOMER Pro produced:

i. an Optimization Results Table summarizing the technical, economic, and environmental performance of each configuration;

ii. hourly time-series data showing PV production, battery state-of-charge, and generator output; and

iii. detailed summaries of fuel consumption, emissions, and system reliability indices (LOLE, LOLP, LOEP).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview of Simulation Output

Following the entry of all technical and economic parameters described in Chapter Three, HOMER Pro performed an optimization to identify the most cost-effective combination of PV array, battery storage, and diesel generator capacities that could meet the faculty's annual electrical load of approximately 737,686 kWh/year**.** The software analyzed thousands of possible configurations and ranked them based on their Net Present Cost (NPC)**,** Levelized Cost of Energy (LCOE)**,** and system reliability**.**

The optimization process produced several feasible systems. Table 4.1 summarizes the most significant configurations.

Table 4.1 - Summary of Key Simulation Results

SYSTEM	**PV(KW)**	**BATTERY (KWh)**	**GENERATOR (KW)**	**CONVERTER (KWh)**	**COE (₦/KWh)**	**NPC (₦)**	**OPERATING COST PER YEAR (₦/y)**
1	525	198.9	85	-	0.0548	522,171	10,892
2	220	205.5	84	-	0.0642	612,685	9,362
3	300	-	220	-	0.3915	3,733,301	266,354

4.2 Economic Performance

The results show that the 525 kW PV + 85 kW Generator + 198 kWh Battery configuration yielded the lowest Levelized Cost of Energy (LCOE) of ₦0.0548/kWh and the lowest Net Present Cost (NPC) of ₦522,171**.** This configuration completely met the faculty's load requirement without using diesel fuel, implying zero fuel cost and a renewable fraction of 100%**.**

Although the initial capital cost of ₦381,365 is relatively high, the total life-cycle cost is significantly lower than all other configurations because of the absence of recurring fuel expenses.

The second configuration (220 kW PV, 84 kW generator, and 205 kWh battery) also achieved 100% renewable operation but with a slightly higher NPC of ₦612,685 and a LCOE of ₦0.0642/kWh, making it economically less favorable than the first.

The third configuration (300 kW PV and 220 kW generator without battery) corresponds to the diesel-dominated baseline, with a very high LCOE of ₦0.3915/kWh and NPC of ₦3.73 million**.** Its operating cost reached ₦266,354 per year, primarily due to fuel consumption of 214,648 liters annually**.**

This highlights the heavy financial burden associated with diesel-only power systems.

The comparison demonstrates that integrating PV and battery storage drastically lowers energy costs by reducing dependency on fuel and maintenance expenditures.

4.3 Reliability and Operational Analysis

The optimized hybrid system exhibited excellent reliability, as it fully satisfied the annual load requirement with zero unmet loads**.** The inclusion of battery storage ensures that surplus solar energy produced during peak sunlight hours is stored and discharged during nighttime or cloudy conditions, thereby maintaining continuous supply.

For the best-performing configuration, the Loss of Load Probability (LOLP**)** and Loss of Load Expectation (LOLE) were effectively zero**,** indicating 100% system reliability**.** The diesel generator**,** although installed, served primarily as an emergency backup and recorded no operational hours within the simulation period.

This result confirms that the 525 kW PV + 198 kWh Battery system can supply uninterrupted electricity to the Faculty of Engineering under typical Benin City solar conditions.

4.4 Environmental Performance

One of the most significant findings from the simulation is the complete elimination of fuel consumption in the top two configurations, resulting in zero carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO) emissions. In contrast, the diesel-only system consumed about 214,648 liters of fuel per year**,** corresponding to approximately 553 tonnes of CO_2 emissions annually (assuming 2.58 kg CO_2 per liter of diesel).

The hybrid design therefore offers not only economic advantages but also major environmental benefits by promoting clean, renewable energy and contributing to the university's sustainability goals.

4.5 Comparative Discussion

A holistic comparison of the three system types (fully renewable, hybrid, and diesel-dominant) is shown in Table 4.2.

Table 4.2 - Comparative Summary of System Configurations

Metric	**Fully renewable (525 KW PV + 85KW Gen)**	**Moderate Hybrid (220 KW PV + 84 KW Gen)**	**Diesel-Dominant (300 KW PV + 220 KW Gen)**
LCOE (₦/KWh)	0.0548	0.0642	0.3915

NPC (₦)	522,171	612,685	3,733,301
Fuel Consumption(L/yr)	0	0	214,648
Renewable Fraction (%)	100	100	9.98
CO_2 Emission (t/yr)	0	0	553

The comparison clearly demonstrates that the fully renewable system is the most technically and economically viable configuration for the Faculty of Engineering. It provides stable, clean, and cost-effective power while eliminating reliance on fossil fuels. The diesel-only setup, while having lower initial cost, proves unsustainable over the system lifetime due to high operational and environmental costs.

4.6 Discussion of Findings

The HOMER Pro simulation successfully identified an optimal standalone hybrid power system composed of:

- **i.** 525 kW Photovoltaic Array
- **ii.** 198 kWh Battery Bank
- **iii.** 85 kW Diesel Generator (as backup)

This system achieved:

- **i.** 100% renewable energy fraction
- **ii.** Zero fuel consumption
- **iii.** LCOE of ₦0.0548/kWh
- **iv.** NPC of ₦522,171

v. Unmet Load = 0% (LOLP ≈ 0)

The findings confirm that a properly sized PV–Battery hybrid system can provide continuous, reliable, and environmentally sustainable electricity to the Faculty of Engineering. Compared to the diesel-only alternative, the hybrid system reduces operating cost by over 95%**,** eliminates annual CO_2 emissions, and offers an economically superior long-term solution.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study successfully evaluated the reliability, economic performance, and environmental benefits of a standalone hybrid energy system integrating photovoltaic (PV), diesel generator, and battery storage for the Faculty of Engineering, University of Benin.

The research employed the HOMER Pro simulation software to design, model, and optimize different system configurations using real load-survey data and local solar resource parameters. The primary objective was to identify the most feasible and cost-effective energy mix capable of supplying continuous and clean power to the faculty.

The simulation results revealed that the optimal configuration consisted of:

i. 525 kW photovoltaic array,
ii. 198 kWh battery storage, and
iii. 85 kW diesel generator (standby).

This system achieved a 100% renewable fraction, Levelized Cost of Energy (LCOE) of ₦0.0548/kWh, and Net Present Cost (NPC) of ₦522,171. It provided reliable, uninterrupted power supply to meet the annual load demand of approximately 737,686 kWh/year, with zero unmet load and no fuel consumption throughout the simulation period.

In contrast, the diesel-only configuration had a LCOE of ₦0.3915/kWh and NPC of ₦3.73 million, with annual fuel use of over 214,000 liters. This confirms that diesel-only systems are both economically unsustainable and environmentally harmful.

The study thus demonstrates that a PV–Battery hybrid system is a technically viable, economically efficient, and environmentally clean solution for powering institutional facilities in Nigeria, particularly in regions with abundant solar energy resources such as Benin City.

5.2 Achievement of Research Objectives

All the objectives outlined at the beginning of this research were successfully achieved through systematic data collection, model development, and simulation using HOMER Pro.

The first objective, which was to design and evaluate an optimized hybrid PV–Diesel–Battery system, was accomplished by developing a complete model of the Faculty of Engineering's energy demand profile and simulating several design alternatives in HOMER Pro. Through the optimization process, a technically feasible configuration of 525 kW photovoltaic array, 198 kWh battery bank, and 85 kW diesel generator was obtained as the most suitable system. The design satisfies the load requirements with no supply interruption and represents a practical and sustainable energy solution for the faculty.

The second objective sought to assess the reliability of the system using indices such as the Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE). The simulation results indicated that the optimized system recorded an unmet-load fraction of 0%, corresponding to negligible LOLP and LOLE values. This demonstrates that the system can reliably supply continuous electricity throughout the year, even during periods of low solar radiation, thereby meeting the reliability target of the study.

The third objective focused on economic analysis to compare the hybrid system with a diesel-only alternative. Results showed that the hybrid configuration achieved a Net Present Cost (NPC) of ₦522,171 and a Levelized Cost of Energy (LCOE) of ₦0.0548 per kWh, far below the diesel-only system's LCOE of ₦0.3915 per kWh and NPC of ₦3.73 million**.** These findings confirm the economic superiority of the hybrid system, as its higher initial investment is offset by the elimination of fuel costs and reduced maintenance expenses over the system lifetime.

The fourth objective was to evaluate the environmental impact of the proposed design. The optimized system achieved a renewable fraction of 100 % and required no diesel fuel, resulting in zero CO_2, SO_2, and NO emissions. In contrast, the diesel-only baseline consumed over 214,000 litres of fuel per year, emitting roughly 553 tonnes of CO_2 annually. Hence, the hybrid design meets the goal of providing a clean, environmentally friendly power source and supports global and national emission-reduction efforts.

The fifth objective involved sensitivity analysis to test the robustness of the system against variations in economic and environmental parameters such as fuel price and solar irradiance. The analysis revealed that the hybrid system remained economically viable even when diesel prices increased or solar availability decreased slightly, demonstrating resilience and adaptability under different operating conditions.

Finally, the sixth objective was to develop an implementation strategy for deploying the system within the Faculty of Engineering. A practical, phased strategy encompassing detailed site assessment, component procurement, installation, monitoring, and future expansion—was formulated to guide real-world application of the research outcome.

In summary, all the specific objectives of the study were fully realized. The results confirm that a properly sized PV–Battery hybrid system can deliver reliable, cost-effective, and sustainable electricity to the Faculty of Engineering, thereby validating the overall aim of the research.

5.3 Recommendations

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

1. Adopt Hybrid Renewable Systems for Institutional Facilities: The Faculty of Engineering and other university departments should consider adopting PV–Battery hybrid systems to reduce dependence on costly and unreliable diesel generation.
2. Battery Technology Advancement**:** Continued investment in advanced storage technologies (such as lithium-ion and flow batteries) should be encouraged to further reduce energy costs and enhance system performance.
3. Capacity Building and Training: Technical personnel should be trained in system maintenance, energy monitoring, and data-driven optimization to ensure long-term sustainability of the installed system.
4. Future Research: Future studies can extend this work by incorporating grid-connectivity options, demand-side management, or other renewable technologies (e.g., wind turbines or biogas) to further enhance reliability and flexibility.

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