

Hybrid Renewable Energy Systems for Nigerian Academic Institutions: A Case Study of the University of Lagos

¹Ibifubara Humphrey, ¹Buhari Farouq Olalekan, ¹Nsikan Ime Obot

¹Department of Physics, University of Lagos, Nigeria.
✉: ihumphrey@unilag.edu.ng; +(234)08034430069

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Abstract:

Affordability and grid stability of electricity remain a major concern for learning institutions throughout sub-Saharan Africa, and Nigeria is not left out. At the University of Lagos, there is indiscriminate grid supply and power load shedding that affects academic processes and research continuity. This current research explores the design and techno-economic viability of a hybrid renewable energy system specific to the energy demand of the university. Various configurations of systems with solar photovoltaic arrays, wind turbines, lithium-ion battery storage, and diesel backup were contrasted using the hybrid optimization of multiple energy resources software. The performance indicators of net present cost, levelized cost of electricity (LCOE), renewable fraction, and percentage of unmet load were contrasted under the actual load profiles as dictated by the academic calendar. Results indicate hybrid system introduced has significant diesel reduction, 83% high renewable penetration, and competitive LCOE of \$0.067/kWh. Sensitivity analysis also verifies system robustness to fuel price uncertainty and seasonal variation in solar and wind resources. Finally, the research attests to the feasibility of hybrid systems as affordable, high-performance options for powering university campuses in the tropics, thus providing an expendable template for energy change in the same campuses.

Keywords: Energy, Solar Panel, Wind Turbine, Affordability, Learning Institution.

1. Introduction

In most developing countries, particularly the sub-Saharan Africa countries, access to reliable and affordable electricity remains a gigantic issue. Nigeria continues to experience unstable grid electricity and ongoing power outages despite having natural energy resources in the country in abundance. The unreliability of the power supply coupled with high energy cost greatly impacts on institutions of learning such as the University of Lagos (UNILAG), whose administrative, research, and teaching activities are disrupted. Studies have shown that space cooling and lighting are major contributors to electricity consumption in academic buildings [1-2]. The University of Lagos has a complex power-hungry infrastructure funded by a combination mix of power generation facilities. These comprise a 132/33/11 kV Power Holding Company of Nigeria (PHCN) substation, diesel generators, solar cells, and battery inverters, with the latter two providing most of campus load [3]. The university campus has high power consumption with a peak load of about 9.0 MW with a lot of diesel generator usage because of insufficient grid supply. Hence, the University of Lagos spends approximately \$300,000 monthly on both diesel generators and grid electricity [4]. Given the energy demands continue to increase owing to increasing digitization, infrastructure growth, and heightened enrollment, the necessity of adopting less expensive and renewable alternative sources of power has to be explored.

The operation of hybrid photovoltaic (PV) /wind power systems under tropical weather has also been encouraging, particularly with the integration of storage facilities and intelligent control schemes. Anuoluwapo and Abolaji [5] affirm that hybrid renewable energy systems (HRES), consisting of several sources of energy such as solar and wind with battery storage and auxiliary back-up such as diesel generators, have received global interest as a green option. The systems benefit from balancing the unpredictability of renewable resources, ensuring energy reliability and reducing environmental footprint. They best suit tropical and coastal regions such as Lagos due to the high irradiation levels of the sun and moderate regimes of wind.

Technological feasibility, economic viability, and efficiency of hybrid renewable systems were rigorously validated through the literature. Compared to grid or diesel-only alternatives, hybrid systems may reduce significant operating costs in the long run, based on the economic evaluation of HRES in the tropics [6]. In the same way, Rominiyi et al. [7], examined HRES deployments within African universities and identified a few key issues, which include the absence of policy, up-front costs, and the absence of technical skills. But they emphasized that these issues can be avoidable with proper planning, which will yield long-term benefits in areas related to sustainability and energy reliability.

In line with findings conducted by Kavadias and Triantafyllou [8], there are possibilities for Nigerian universities to embrace renewable energy as long as donor aid

and effective energy policy exist. Even in the face of such encouraging findings, there is very limited actual implementation. Most institutions remain dependent on expensive and environmentally unfriendly diesel generators. As argued by Dodo et al. [9] the use of hybrid systems would greatly reduce fossil fuel consumption and solar intermittency, especially if there is reliable wind action during nighttime or cloudy skies. Also, many individuals are using optimization software such as Hybrid Optimization of Multiple Energy Resources (HOMER) Pro to simulate and optimize hybrid system design. While reviewing computer programs of HRES modeling, Oladigbolu et al. [10] revealed that HOMER is particularly helpful in the fact that it can account for various configurations, load profiles, and sensitivity parameters.

Apart from conventional supply restrictions, the grid electricity dependence of the University of Lagos is economically unwise and inadequate to satisfy the increasing energy needs of the campus. The university experiences extremely high peak loads over time of learning, examination, and holiday periods. Although some individual stand-alone solar PV systems have been placed, a wide-scale campus-level installation of a hybrid system has not yet occurred. For bridging this knowledge gap, this research provides the techno-economic design of a battery backup diesel-assisted hybrid solar-wind power system. Simulation was carried out on the system using HOMER Pro software, and important performance indicators such as Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), and Renewable Fraction (RF) were compared and analyzed with diesel standalone and grid standalone energy systems.

The main aim of this study is to establish whether a hybrid renewable energy system would be technically and economically viable for UNILAG's requirements. It specifically aims to discover the least-cost option with the maximum percentage of renewable energy contribution and minimum long-run operation cost. This research adds to the body of literature documenting sustainability in higher education and provides a realistic model for other sub-Saharan African universities to achieve energy self-sufficiency and environmental care.

In the long run, the implementation of hybrid renewable systems is a measure to forestall recurring energy issues at the university. By creating simulation-driven design from real patterns of energy utilization, accessible resources, and institutional sustainability objectives, this research contributes to scholarly thought and real-world application. Implications can be implemented in policy-making, investment promotion, and as a model that can be emulated for building design energy resilience within the educational institutions of the country.

2.0 Materials and Methods

The study uses a techno-economic simulation-based method to assess the feasibility of a solar-wind hybrid power system for the University of Lagos. The design process consists of four key steps: (i) site and load analysis, (ii) system design configuration, (iii) simulation using HOMER Pro, and (iv) economic and performance assessment.

2.1 Site and Load Evaluation

At 6.52°N latitude and 3.40°E longitude, UNILAG enjoys good climatic conditions for the implementation of renewable energy. The site has a mean solar irradiance between 4.5 and 6.5 kWh/m²/day and wind speeds between 2.5 and 4.5 m/s at a hub height of 10 m, with better values at higher altitudes. Historical patterns of electricity consumption and institutional schedules guided the development of seasonal load profiles. This includes peak times of demand during exams and registration, and off-peak times during holidays. The resultant load profile indicates a mean daily demand of about 3,400 kWh/day.

2.2 System Design Configuration

The proposed hybrid power system consists of a 775 kW solar photovoltaic (PV) array, selected based on the available rooftop and ground areas, the solar resource of the site, and the building code requirements of the locality. It is supplemented by a wind power component consisting of multiple small-sized turbines with a cumulative capacity of 200 kW, each optimally tuned to the mean wind speeds of the region. In order to improve reliability and provide an uninterruptible power supply, especially during off-peak generation times, the system is equipped with a 1.3 MWh lithium-ion energy storage facility. The storage has several advantages: electrical load management, provide night-time power, and energy production buffering. Apart from this, a 300 kW diesel generator has also been provided in the system as a standby power for power shortfall and deep load shifting at the peak demand period. Grid connection has also been provided in the system which not only facilitates energy purchase in the period of renewable scarcity but also sell-back in the future, thus offering operational flexibility.

Typically, this is an optimized configuration in the framework of reliability, sustainability, and capital investment balance, and it constitutes a best-practice strategy for hybrid renewable systems in tropical university environments. According to Aguilar et al. [11], these designs are institutional best practices for resilience and energy efficiency (Figure 1).

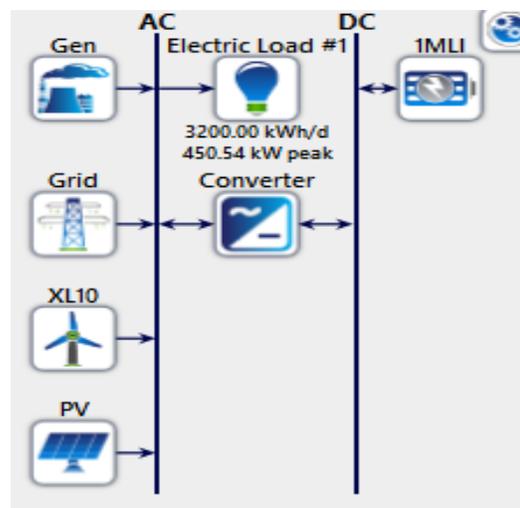


Figure 1: Hybrid renewable system configuration analyzed in HOMER

2.3 Simulation Parameters and Optimization

The hybrid system was simulated with HOMER Pro using the input data of National Aeronautics and Space Administration-Surface meteorology and Solar Energy (NASA-SSE) and HOMER wind resource databases. Component prices, performance specifications, and economic assumptions (i.e., 10% discount rate) were regionally benchmark-based and vendor-specific [12]. Sensitivity analysis was conducted on most important variables (i.e., fuel price, replacement battery price, and tariffs for electricity). Optimization was carried out to minimize NPC and LCOE and optimize penetration of the renewable source.

3.0 Results and Discussion

Results from simulation give a general estimation of the technical and economic performance of the hybrid system under site-specific conditions.

3.1 System Configuration and Output

The most appropriate hybrid configuration determined by HOMER Pro consists of a 200 kW wind turbine array (ten 20 kW units), 300 kW diesel generator, 1.3 MWh lithium-ion battery bank, 775 kW solar PV array, and grid. This configuration, determined by using a multi-objective optimization method, has high renewable energy penetration and system reliability with the NPC and LCOE minimized. Based on historical campus loading profiles, the system can sustain an average daily load of about 3,400 kWh accounting for academic seasonality. NASA-SSE simulation and HOMER wind data validation are in affirmation that the design has an NPC of \$1.35 million, LCOE of \$0.067/kWh, renewables fraction of 83%, 0% unmet load, and 6.7% excess electricity, thus providing stable and low-carbon electricity supply over a 25-year lifespan.

3.2 Resource Utilization and Load Profile

The University of Lagos operates a dynamic power demand profile based on academic schedules, administrative activities, and variable occupancy with a mean daily load of approximately 3,400 kWh/day with large variability between semesters of high activity and holiday times. To better model this volatility, HOMER Pro simulation was incorporated with seasonal demand modeling so more realistic component sizing and performance analysis could be performed. The hybrid power system takes advantage of Lagos' favorable solar irradiance and moderate wind speeds through the use of solar data from the SSE platform of NASA and wind inputs from internal HOMER models. The solar and wind resources enjoy complementary seasonal synergy throughout the year, providing balanced supply of energy, where solar prevails in the dry season and wind supplements it in the wet seasons. The system is always meeting base load at periods of low renewable generation, balances peak demand well, stabilizes supply with battery storage, and has hardly any grid input dependency. Such synchronization of the availability of resources and energy needs emphasizes the reliability of the hybrid system and justifies the vital role provided by climate-sensitive and demand-responsive hybrid design.

3.3 Renewable Resources Performance

Temporal variability and availability of wind and solar resources in Lagos, Nigeria, are the most important drivers of the performance of the proposed hybrid renewable system. System dispatch policy, sizing, and economic viability all hinge on proper modeling of the resources. Data of twenty-two (22) years on solar radiation were used in this research based on the NASA Surface Meteorology and Solar Energy (SSE) database, while HOMER Pro typical meteorological year (TMY) databases were used for simulating the wind speed.

3.3.1 Solar Resources Profile

Lagos experiences uniformly high levels of global horizontal irradiance (GHI) ranging from 4.5 to 5.5 kWh/m²/day throughout the year, while receiving the optimal solar conditions from November through March due to clearer skies and lower cloud cover. The propitious climatic spectrum favors PV installations to contribute tremendously towards power generation, producing approximately 55 to 60% of the total electricity output annually. Daily PV generation is at its best between the months of January to March (this is a period of dry season, associated with longer sunshine duration, clear skies, low cloud cover and high solar irradiance) and dips by a significant amount during the months of August and September due to increased cloud cover. Storage in batteries also contributes to system reliability by day-night balancing of loads storing electricity generated during the day and selling it back on sunny as well as cloudy days. It reduces dependence upon grid supply or standby diesel and amounts to a sure and uninterrupted source of energy. In general, the solar resource abundance in Lagos justifies the feasibility of solar-dominant hybrid systems for tropical universities.

3.3.2 Profile of Wind Resources

Wind energy is an important back-up source of power, especially during times of weak solar generation in Lagos. Mean wind speeds at 10 m above ground level vary between 3.5 and 4.5 m/s and are aided by the efficiency of XL10 20 kW turbines, and wind resources are moderate but adequate to feed hybrid power applications. Wind turbines supply approximately 15 to 20% of the system's yearly electricity generation. Unexpectedly, the wind speeds are highest between May and September, the same interval for the rainy season and seasonally low solar irradiance. It is this inverse relationship which makes wind power complement solar photovoltaics so well, especially during months like July and August when solar generation is lowest. In the southern Nigeria, especially in Lagos, this is a period of peak rainy season, associated with increased atmospheric moisture, cloud cover and reduced solar irradiance. The complementary roles of these two renewable technologies guarantee a high level of renewable energy fraction year-round. As confirmed by Ayua and Emeteri [13], solar-wind hybrid systems have better performance in coastal West African climates, indicative of their strategic significance in planning sustainable energy systems.

3.4 Monthly Electric Production

The mean monthly power generated by hybrid system's solar PV, wind power, diesel generator, and grid are represented

in Figure 2 below. The graph indicates solar PV is the dominant source of power every year, especially during November to April when solar irradiance is highest. Alternatively, wind energy can compensate for seasonally low solar output by topping up output during the May to September months that are wetter.

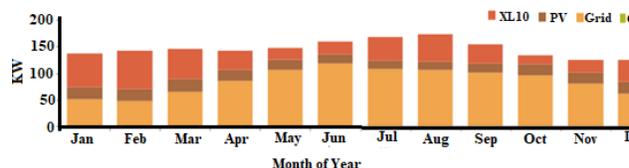


Figure 2: Monthly Average Electricity Production

The operation of the diesel generator is minimal and restricted to only two months, i.e., August and October, indicating intermittent support during times of drought. The system independence is indicated from the persistently low grid supply. With seasonality complementarity between wind and solar and reduced reliance on non-renewables, the system indicates a generalized well-synchronized renewable generation pattern. Such observations are in line with other tropical hybrid energy research [14].

3.5 PV Power Distribution by the Day and Hour

The daily and hourly PV power output distribution for a year is presented in the heat map below (Figure 3). A clear diurnal behavior is present, with production always at maximum during 11:00-15:00, i.e., when solar irradiation is highest. As evident from the bright orange and yellow bands, the color intensity indicates that output is usually between 84 kW and 140 kW, particularly on clear days. This midday peak output concentration indicates the extent to which the system can accommodate energy peak hours during the day [15].

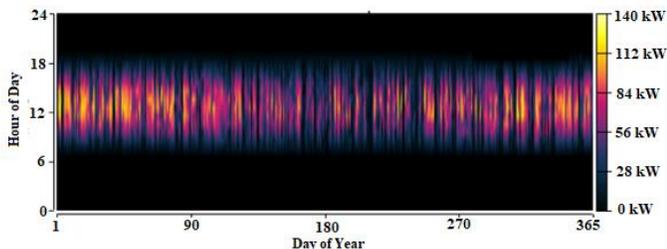


Figure 3: PV Power Output

Also observed is the seasonal variation. The heat map represents a dense band-like pattern during the peak summer (approximately Days 150 to 250), which signifies uniform solar conditions during Lagos' dry season. Generation trend is then less anomalous in the late and early seasons of the year (Days 270–365 and 0–90), indicating the effect of moist and rainy weather normally associated with the wet season. However, the system still provides daily energy but of lower amplitude. The intermittency experienced, thus, adds to the importance of incorporating complementary sources of power, despite the fact that PV system produces a consistent and good amount of energy throughout the year. Integration with energy storage and

wind generation modules addresses PV intermittency, increasing system-wide reliability.

3.6 Wind Turbine Power Distribution Daily and Hourly

The heat-map in Figure 4 is a representation of the hourly rate of wind turbine generation for a year with color saturation mapping to level of production. While the x-axis contains all 365 days, the y-axis fits 24 hours of the day. It can be seen at first glance that since the generation from wind is highly irregular and lacks the pattern of being regular by day is self-evident. Because of their intrinsic dependence on random atmospheric conditions, wind resources are associated with this intermittency. The black regions of the figure correspond to hours of diminished or zero power, and blue to red shades correspond to growing levels of power, culminating at 1,200 kW.

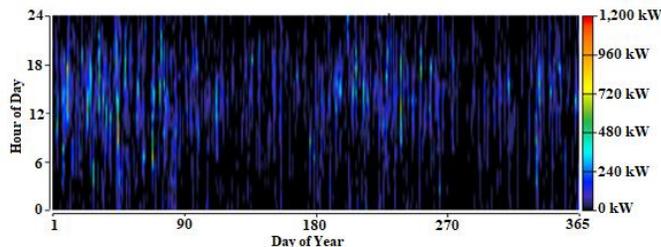


Figure 4: Wind Turbine Power Output

Besides, there are discernible but faint seasonal patterns. Day 60–150 and day 250–330 experience more activity, aligned roughly with Lagos's transition from rainy to dry season. These times presumably correlate with increases in mean wind speeds during seasons due to local climate change. The plot however reveals that generation by the wind continues to be highly unpredictable and fluctuates randomly by day and year. Direct scheduling of electricity is complicated by the fact that wind power never reaches its peak at a particular hour, unlike solar power whose schedule operates on a daily periodicity [16]. The graph indicates that although maximum values can be produced by the wind turbines theoretically, the system is never close to capacity. Most of the operating period is between 0 and 480 kW, so the capacity of the system is not fully utilized. Regional turbulent impacts or wind supply limitations at the installed hub height may be the reasons for this. Therefore, wind power assists the hybrid system in a secondary way rather than a primary way. But since it enhances system strength and reduces dependency on fuel-fired generators or grid imports, its implementation is significant, particularly in case of solar outages [17].

3.7 Average Monthly Battery State of Charge (SOC)

The average one-year SOC of the battery storage system monthly is shown in Figure 5. As seen, the SOC is nearly 100% throughout the year. This means that the battery bank is always charged as it barely shows any discharging operation. This kind of performance indicates either a reserve within the generation of renewables against the load or a system setting that favors other sources of power like the grid or the diesel generator when renewables are insufficient [18].

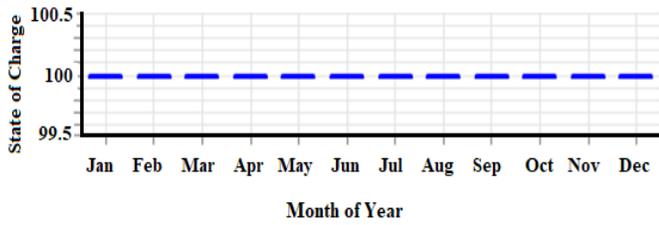


Figure 5: Stable Monthly Battery State of Charge

A very high state of charge may indicate under-utilization of the battery system, but in general, it is desirable for battery life and system reliability. It is problematic for potential over-sizing if the storage capacity hardly gets utilized. In order to provide more actively stored energy in high-load or grid failure situations, it can thus be a chance to upgrade the system through battery bank re-sizing or control strategy modification [19]. Additionally, effective season balancing is defined by consistency of the SOC trend in all months. This stability can be attributed in large part to the hybrid nature of the system, where wind and solar are combined in a manner that offsets seasonal variability. Stable energy management practices avoiding deep discharging or heavy reliance on a single source are also considered. Therefore, while underutilized, the battery system is critical in ensuring energy security and offsetting occurrences of transient oscillations.

3.8 Monthly Fuel Consumption

The month-to-month trend of the use of diesel in the hybrid system, evident in Figure 6, is the best illustrative result: no diesel was consumed at all throughout the simulation. This result demonstrates the efficiency of the system and how the storage and renewable energy parts were properly integrated into the system. This verifies the sufficiency and reliability of the hybrid design by supplying the energy requirement throughout the process without accessing the fossil fuel standby.

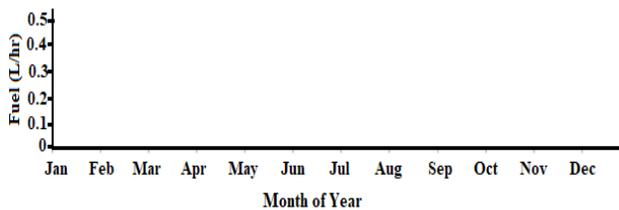


Figure 6: Zero Monthly Fuel Consumption

Primarily, the sum total of the output from solar PV and wind turbines was always adequate for the year, regardless of shifting seasons, and secondarily, possessing a strong 1.3 MWh lithium-ion battery bank provided uninterrupted energy balancing by effectively storing excess energy and dumping it during periods of lesser renewable output. Together, the two major components constitute a strong and independent energy supply system. In addition, the HOMER Pro optimization approach, which prefers low-cost and low-emission sources of energy, is precisely in harmony with this finding. The system saves on running expenses and enhances its environmental friendliness via the elimination of the use of diesel fuel. Lastly, consistent with the given simulation background, the ability of the hybrid

system to offer clean, stable, and inexpensive power is brought to light via the complete elimination of fuel consumption [20].

3.9 Economic Performance and Cash Flow

The cash flow from the system for a 25-year life-cycle of the project is provided below in Figure 7, along with details of capital investment, operating expenses, replacements, and salvage value. High capital investment of \$1.1 million was made to purchase and install the solar PV system, wind turbines, lithium-ion batteries, diesel generator, and control items. Studies have also investigated hybrid renewable energy systems (HRES) made up of solar PV, wind turbines, batteries, and diesel generators to lower fossil fuel consumption and improve grid stability. HRES comes with enormous initial costs ranging from \$1.02 million to \$6.58 million but provides long-term economic gains [21][22].

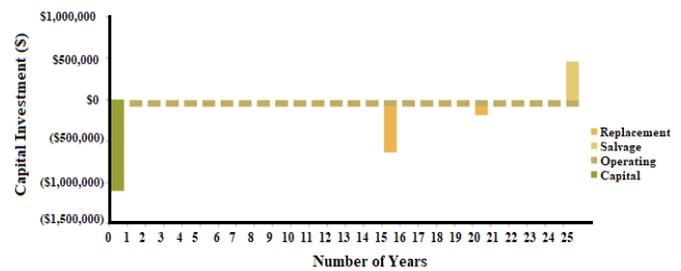


Figure 7: Life-Cycle Cash Flow Distribution of the Hybrid Renewable Energy System Over a 25-Year Project Horizon

The planned replacement of battery storage units and partial generator maintenance in Year 15, halfway through the project's lifespan, resulted in a noticeable replacement cost. Around Year 20, minor operating costs start to show up, most likely related to system maintenance. The project ends in Year 25 with a positive salvage value, which partially offsets total costs and reflects the assets' remaining value at the end of their useful lives. The financial trajectory shows that despite the high initial investment, the system's high renewable fraction results in low ongoing operating and maintenance costs. This pattern is in line with the findings of Kwon et al. [23], who pointed out that when fossil fuel dependence is reduced, capital-intensive hybrid renewable systems typically show positive long-term economic returns. Additionally, the salvage value increases project viability, bolstering hybrid systems' viability in educational institutions with steady, long-term energy requirements.

4.0 Discussion

The efficiency of the suggested grid-connected solar-wind hybrid power system for the University of Lagos was exhaustively analyzed based on HOMER Pro simulation in technical, economic, and environmental parameters. Solar PV was the highest and most reliable source of power, especially during dry periods, while wind power, which has a smaller mean capacity and is more volatile, augmented solar during low irradiance periods efficiently. Battery storage was quite important to reliability, despite its ever-high state of charge suggesting potential over-sizing. However, the diesel generator was not in use, thus establishing that the university's power

requirement throughout the whole year was adequately catered for by renewable and grid supplies. Economically, while the system had a high initial capital cost, its long-term cost profile was low as it has low operating and replacement costs. The Levelized Cost of Energy (LCOE) was kept low, especially in the case of increasing fuel prices or fluctuating grid availability, due to the optimized HOMER Pro configuration [24]. On the environmental side, the system realized significant CO₂, SO₂, and NO_x emission savings that are in line with global sustainability goals and Nigeria's clean energy vision [6]. Sophisticated dispatching methods and load-following mode of operation maximized efficiency, taking advantage of flexible grid reliance during peak times [25]. Lagos's climatic conditions of high solar radiation and average wind levels and nonsystematic institutional load patterns guided the system design. Notwithstanding, these simplifying assumptions involve equal energy costs and basic demand modeling in the study, they constitute limitations to the analysis. Hence, real-world field data should be used to validate the assumptions, and consultations with appropriate stakeholders should be undertaken to ensure the validity and applicability of the system design and economic estimates [26-27]. Generally, the results are validated by similar studies in African organizations and off-grid communities demonstrating the technical viability, economic soundness, and environmental gains of hybrid renewable systems [28]. The research therefore forms a strong basis for the installation of renewable energy systems in Nigerian university campuses.

5.0 Conclusion

This research extensively evaluated the techno-economic viability of a hybrid renewable energy system (HRES) comprising solar photovoltaic (PV), wind turbines, lithium-ion battery, and diesel generator for grid supply in the University of Lagos. The need to undertake this research was triggered by the university's persistent energy challenges, such as high diesel

consumption, inconsistent grid supply, and increasing energy demand from academic development and digital infrastructure. By using a detailed model created in HOMER Pro, the research proved that a hybrid system size of 775 kW PV, 200 kW wind capacity, 1.3 MWh storage, and 300 kW diesel backup was able to supply daily energy need reliably with an 83% high renewable fraction, zero unmet load, and cost-effective Levelized Cost of Electricity (LCOE) of \$0.067/kWh. The system completely avoided the use of diesel fuel throughout the simulation period, which is a testament to its environmental and operational reliability. Seasonal variations in energy supply indicated solar predominance in dry months and wind complementarity in the rainy season, as anticipated, justifying system resilience to climate fluctuations. Costing found that while initial capital expenditure was high, long-term fuel and maintenance cost savings made economic viability with a 25-year lifespan justifiable. The results confirm the evidence that hybrid energy systems are a safe, affordable, and eco-friendly choice for tropical universities and must be included in campus energy transition policies.

Declarations

There is no conflict of interest

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