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Techno-Economic Performance Assessment of Grid-Connected Hybrid Renewable Energy Systems for Sustainable Institutional Power Supply

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Abstract **Original Research Article**

The reliability of energy supply to institutional facilities in Nigeria has remained constrained by inadequate grid availability and continued dependence on diesel generation. In this study, the electrical demand characteristics and techno-economic performance of a grid-connected hybrid renewable energy system was evaluated using measured load data and HOMER Pro simulation. An energy audit was conducted to establish the hourly electricity demand profile. Furthermore, site-specific solar and meteorological data were incorporated into the simulation. The measured load profile showed an average demand of 632.17 kW, a peak demand of 987.40 kW and an estimated annual electricity consumption of approximately 5.54 GWh. The techno-economic assessment revealed that PV–battery–diesel–grid configuration is the most favourable system. Simulation results showed that PV generation supplied the dominant share of energy whereas battery storage provided energy balancing with the diesel generator operating intermittently as a backup source. The economic assessment showed a substantial reduction in cumulative cost compared with the base-case electricity supply. The hybrid system reached approximately US$1.7 million over 25 years compared with about US$6.6 million for the base case. The findings demonstrate that integrating PV generation and battery storage with existing grid and diesel infrastructure can substantially reduce conventional energy dependence while improving the economic performance and reliability of electricity supply.

Keywords: photovoltaic system, battery storage, diesel generator, hybrid renewable energy system, HOMER Pro, techno-economic assessment.

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1.0 INTRODUCTION

In recent times, there has been an increasing energy global demand. This comes amidst increasing concerns over climate change and the depletion of fossil fuel resources. This has intensified efforts toward the adoption of sustainable energy technologies. Rapid industrialization, population growth and urban expansion continue to place

unprecedented pressure on existing energy infrastructures particularly those in developing economies where energy supply often fails to meet demand (Kaygusuz, 2012). Therefore, governments, industries and research institutions are increasingly investing in renewable energy technologies to improve energy security, reduce greenhouse gas emissions and accelerate the transition toward low-carbon energy systems. Among the available renewable energy resources, solar photovoltaic (PV) technology has experienced remarkable growth due to its declining installation costs, technological advancements, modularity and widespread resource availability. However, the inherent intermittency of solar energy presents significant operational challenges when PV systems are deployed as standalone power sources (Rajendran et al., 2025). This necessitates complementary technologies that can ensure reliable and continuous electricity supply.

Hybrid renewable energy systems (HRESs) integrate renewable energy technologies with energy storage devices, conventional backup generators and utility grids. They have emerged as one of the most promising approaches for addressing the reliability challenges associated with renewable energy integration. HRESs enhance system flexibility, supply reliability and renewable energy utilization (Giedraityte et al., 2025). Recent studies have shown that grid-connected hybrid systems offer operational advantages by allowing electricity exchange with the utility network thereby improving system resilience while minimizing lifecycle costs (Eissa et al., 2026; Adeyinka et al., 2024; Atawi et al., 2022). The incorporation of battery energy storage systems improves operational flexibility by storing excess renewable energy during periods of high generation and supplying electricity during periods of insufficient renewable output or peak demand. Consequently, hybrid renewable energy systems are increasingly being adopted across residential, commercial, industrial, healthcare, educational and governmental facilities as practical solutions for sustainable electricity supply. Furthermore, an important category of energy consumers is the institutional buildings. This is because they depend heavily on continuous and reliable power supply to support administrative activities and other critical services.

In many developing countries, institutional facilities are frequently affected by unreliable grid electricity, characterized by recurring outages, voltage fluctuations, and inadequate generation capacity. These deficiencies often necessitate prolonged operation of diesel generators which results in increased operational costs, fuel consumption, greenhouse gas emissions and maintenance requirements (Issa et al., 2029). The growing demand on sustainable institutional energy management has stimulated considerable interest in hybrid renewable energy systems capable of reducing dependence on conventional generators while ensuring uninterrupted energy supply (Olatomiwa et al., 2016). Beyond improving reliability, the adoption of hybrid renewable energy systems offers opportunities for reducing operational expenditures, enhancing environmental sustainability and supporting national commitments toward clean energy development. Hybrid renewable energy technologies have been accompanied by significant advances in modelling and simulation tools for system evaluation (Sinha and Chandel, 2014). Among these, the Hybrid Optimization Model for Electric Renewables (HOMER) has become one of the most widely used software platforms for the techno-economic assessment of hybrid energy systems. HOMER enables comprehensive evaluation of numerous system configurations by considering renewable resource availability, electrical load characteristics, equipment specifications, operational constraints and lifecycle economic indicators. Recently, investigations into hybrid energy systems for rural electrification, university campuses, healthcare facilities, commercial buildings, industrial applications and isolated microgrids have been conducted by several researchers (Pérez et al., 2024). These studies consistently report that integrating photovoltaic systems with battery storage and auxiliary generators can significantly enhance supply reliability compared with conventional diesel-based electricity generation.

However, a considerable proportion of these studies focus primarily on rural communities, off-grid

settlements or residential applications with a few addressing the unique operational characteristics of institutional buildings. Furthermore, many existing studies rely on estimated or synthetic electrical load profiles rather than measured energy consumption data obtained through comprehensive energy audits. Such assumptions may not adequately capture the temporal variations associated with actual institutional energy demand thereby reducing the practical applicability of the resulting system recommendations. Although, techno-economic indicators such as net present cost (NPC) and levelized cost of energy (LCOE) are routinely reported, limited attention has been given to detailed operational performance analyses of individual hybrid system components. On the contrary, more comprehensive evaluation of these operational characteristics is essential for understanding system behaviour under realistic operating conditions and for supporting informed decision-making regarding institutional energy investments (Hung et al., 2024).

This study therefore presents a techno-economic performance assessment of grid-connected hybrid renewable energy systems for sustainable institutional power supply. Furthermore, the operational performance of the selected hybrid system is assessed through detailed analyses of energy production, photovoltaic contribution, generator operation, battery state of charge, inverter performance, grid electricity exchange and lifecycle economic indicators. The findings provide valuable insights into the application of hybrid renewable energy systems for improving energy reliability, reducing operational costs and supporting sustainable energy management in institutional buildings.

2.0 MATERIALS AND METHODS

2.1 Study Area

The Energy Commission of Nigeria (ECN) headquarters located in Abuja; Nigeria was used as the study area. The facility comprises of administrative offices, research laboratories, conference rooms, and auxiliary service units all of which require a reliable energy supply for continuous operation. Energy demand within the facility is primarily met through the national grid, supplemented by a diesel generator during periods of grid outages. However, the unreliable nature of grid electricity which averages approximately four hours of daily availability, necessitates frequent operation of the standby diesel generator. This results in increased operating costs and fuel consumption. This operating condition makes the ECN headquarters an appropriate case for evaluating the performance of grid-connected hybrid renewable energy systems. Abuja, Nigeria possesses favourable solar energy resources throughout the year making photovoltaic (PV) technology a suitable renewable energy option. Meteorological data were obtained from the Nigerian Meteorological Agency (NiMet) database and incorporated into HOMER Pro to simulate the renewable energy resource available at the study location.

2.2 Energy Audit and Load Assessment

A detailed energy audit was conducted to determine the electrical demand characteristics of the ECN building. The audit involved a comprehensive inventory of all electrical appliances and equipment. The rated power, quantity, operating schedules, and daily utilization periods of each appliance were documented to estimate the building's electricity demand. Energy consumption was measured using an ADL 400 three-phase DIN rail energy meter together with a Serial ENERtech 500 wattmeter to obtain representative load measurements (Pălăcean et al., 2024). The collected data were processed to determine the average hourly energy demand.

2.3 Hybrid Renewable Energy System Configuration

The hybrid renewable energy system consisted of a photovoltaic (PV) array, diesel generator, lead-acid battery bank, bidirectional converter and utility grid connection. The photovoltaic array served as the primary renewable energy source. Excess PV generation was directed to the battery bank for storage or supplied directly to the connected load

whenever generation exceeded demand. A CAT 500 kVA diesel generator was incorporated as an auxiliary generation unit to ensure uninterrupted electricity supply during periods of insufficient renewable generation or battery depletion. The utility grid served as an additional energy source whenever required thereby improving system reliability and operational flexibility. A bidirectional ABB MGS100 converter enabled power exchange between the alternating current (AC) and direct current (DC) buses (Belouda et al., 2022). This facilitates efficient charging and discharging of the battery system while maintaining stable power delivery to the connected load.

2.4 System Modelling Using HOMER Pro

The hybrid renewable energy system was modelled using HOMER Pro Version 3.16.2. The measured load obtained from the energy audit was imported into HOMER Pro as the primary demand profile. Meteorological data comprising monthly average solar radiation and ambient temperature were incorporated to characterize the renewable energy resource at the study location. Technical specifications, capital costs, replacement costs, operation and maintenance costs, equipment lifetimes, and operational constraints for the photovoltaic array, diesel generator, battery storage system, converter, and utility grid were defined based on manufacturer specifications and published literature (Hüner, 2025). Economic assumptions adopted during the simulations included a project lifetime of 25 years, an annual discount rate of 8% and an inflation rate of 27%. HOMER Pro evaluated numerous feasible system configurations and ranked them according to their techno-economic performance with the optimal configuration selected based on the minimum Net Present Cost (NPC) while satisfying the energy demand.

2.5 Mathematical Models of System Components

The mathematical models implemented in HOMER Pro were used to estimate the operational performance of the individual components of the hybrid renewable energy system.

2.5.1 Photovoltaic array

The energy output of the photovoltaic array was determined using equation 1.

$$P_{pv} = P_{Npv} \times \frac{G}{G_{ref}} \times [1 + K_t \times ([T_{amb} + \frac{NOCT-20}{800}] \times G - T_{ref})] \quad (1)$$

Where P_{Npv} is the rated power of the PV system. G and G_{ref} represent solar radiation at time t and at standard conditions, respectively. T_{amb} and T_{ref} are the ambient temperature at time t and NOCT is operating condition of the PV at standard conditions respectively. K_t is the temperature coefficient of power and its value depends on the PV panel's technology.

2.5.2 Diesel Generator

The hourly diesel fuel consumption was estimated using equation 2.

$$F_{cons} = a.P_{DG}(t) + b.P_{DG_r} \quad (2)$$

Where P_{DG} (t) is the power generated by DG (kW) at each hour (t), F_{cons} is fuel consumption 33(L/h), P_{DG_r} is the rated power of DG generated at each hour (t), a and b are constants (L/kW), which represent the coefficients of fuel consumption.

2.5.3 Battery Storage

The battery state of charge was updated based on the charging and discharging processes while considering the battery efficiency, depth of discharge and converter efficiency. The battery capacity was constrained between the maximum storage capacity and the minimum allowable state of charge determined by the specified depth of discharge (Kim and Shin, 2023).

2.5.4 Converter

The converter efficiency was determined using equation 3.

$$\eta_{cnv} = \frac{P_{output}}{P_{input}} \quad (3)$$

Where P_{output} and P_{input} are the output and the input power from/to converter, respectively.

2.6 Techno-Economic Performance Assessment

The performance of the hybrid renewable energy system was assessed using key techno-economic indicators generated by HOMER Pro. The Net Present Cost (NPC) was regarded as the primary economic criterion for selecting the optimal system configuration. The Cost of Energy (COE) was used to evaluate the average unit cost of energy supplied by the hybrid energy system and was calculated using equation 4.

$$COE\left(\frac{\$}{kWh}\right) = \frac{C_{Anualized}}{E_{served}} \quad (4)$$

Where $C_{Anualized}$ are the total annualized cost and $E_{served}$is the annual electrical energy supplied to the load.

3.0 Results and Discussion

3.1 Load Characteristics of the Institutional Building

Figure 1-3 presents the resulting load characteristics for the study area selected. This provided the basis for sizing and evaluating the hybrid renewable energy system.

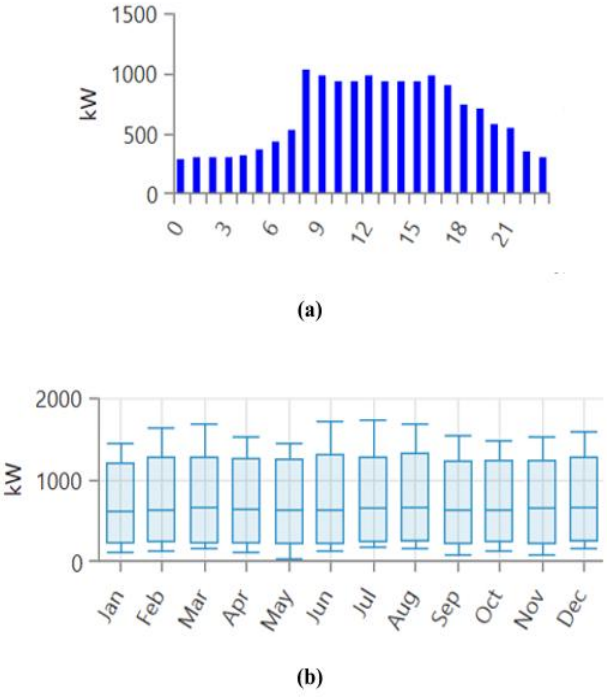


Figure 1: Load profiles for Energy Commission of Nigeria as generated by HOMER: (a) Daily and (b) Seasonal

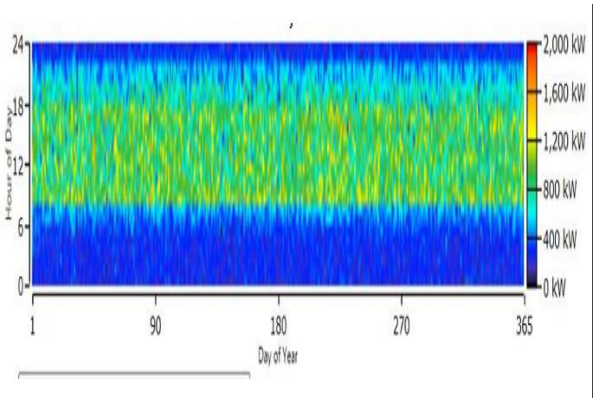


Figure 2: Yearly Load Profile for Energy Commission of Nigeria as generated by HOMER.

The average daily load profile of the ECN building is presented in Figure 1(a). The energy demand remained relatively low during the early hours of the day (00:00–05:00 h) with an average demand of approximately 300 kW. This phenomenon can be attributed to the operation of only essential services such as security systems, emergency lighting and other continuously operating equipment within this period (Yang et al., 2016). An energy demand increase was observed from approximately 06:00h suggesting the commencement of normal administrative activities as the reason for this sharp increase. The load rose steadily during the morning period before reaching its maximum value of approximately 1 MW during normal office hours. The high daytime demand persisted until approximately 17:00 h, after which the energy consumption gradually declined with reduced occupancy and the shutdown of non-essential electrical equipment. However, the building maintained a substantial nighttime base load indicating the continuous operation of critical electrical installations throughout the day.

The energy demand observed in figure 1 (a) matched closely to the period of maximum solar irradiance in Abuja. This complementary relationship between solar resource availability and peak energy demand provides favourable operating conditions for photovoltaic energy generation. This enables a significant proportion of the daytime load to be supplied directly by solar power (Rajendran et al., 2025). Furthermore, the dependence on diesel generation and electricity purchased from the utility grid can be substantially reduced during daylight hours thereby improving both the economic and environmental performance of the hybrid renewable energy system. The seasonal variation in electricity demand (see figure 1(b)) indicates that the ECN building maintains relatively stable energy consumption throughout the year. Although moderate fluctuations are observed across the different months, the median monthly load remains nearly constant suggesting that the building's energy demand is primarily governed by regular institutional activities rather than seasonal occupancy changes (Heidarinejad et al., 2017). The relatively narrow spread of the monthly load distributions demonstrates that the facility experiences consistent energy demand throughout the year, thereby simplifying hybrid system sizing and enhancing the predictability of system operation.

The annual load profile generated by HOMER Pro (see Figure 2) confirms the continuous nature of energy consumption within the ECN building. The heat-map representation shows the hourly load variation over the entire year. Here, higher energy demand is consistently concentrated between approximately 07:00 h and 18:00 h. The persistence of these high-load periods throughout the year reflects the regular working schedule of the institution and indicates that the demand pattern exhibits minimal seasonal disruption. The absence of

prolonged low-demand periods shows that the facility requires a reliable and uninterrupted electricity supply throughout the year. This phenomenon reinforces the suitability of adopting a grid-connected hybrid renewable energy system capable of balancing renewable generation, battery storage, diesel backup and utility grid support.

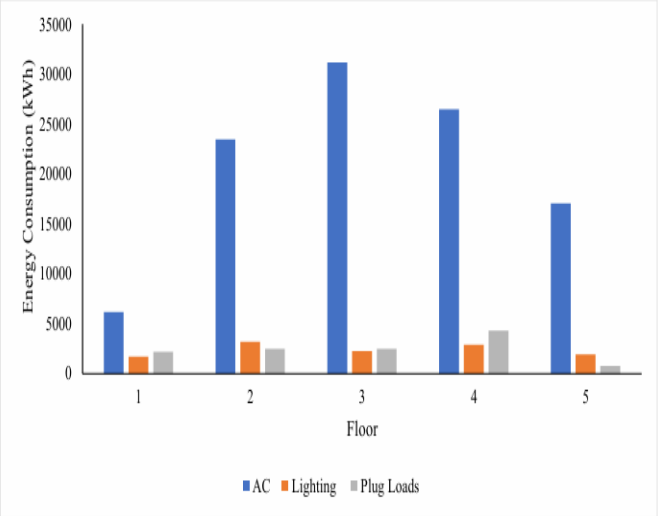


Figure 3: Total Energy Consumption in the ECN Building

Similarly, Figure 3 presents the distribution of annual energy consumption among the major end-use categories within the five floors of the ECN building. Air-conditioning systems account for the largest proportion of electricity consumption on every floor exceeding the energy requirements of lighting and plug loads. The third floor recorded the highest overall electricity consumption followed by the fourth and second floors. However, the dominance of air-conditioning loads shows the tropical climatic conditions of Abuja, where mechanical cooling constitutes a major component of institutional energy consumption. On the other hand, lighting and plug loads contributed comparatively smaller proportions of the total energy demand although their consumption remained relatively consistent across the building. The dominance of cooling loads has important implications for the operation of the hybrid renewable energy system (Wang et al., 2024). Since air-conditioning demand reaches its highest levels during periods of intense solar radiation, photovoltaic electricity generation can effectively offset a substantial fraction of the building's peak energy demand. This natural coincidence between solar energy availability and cooling requirements enhances photovoltaic utilisation, reduces generator operating hours, lowers diesel fuel consumption and improves the overall economic viability of the proposed hybrid energy system.

3.2 Techno-Economic Performance of the Optimal Hybrid Energy System

The techno-economic performance of the hybrid renewable energy system was evaluated using HOMER Pro for a 25-year project lifetime. The simulation identified the optimal system

configuration based on the minimum net present cost (NPC) while ensuring reliable energy supply to the ECN building. The selected configuration comprised a grid-connected photovoltaic (PV) array, a CAT-500 diesel generator, a lead-acid battery bank and an ABB bidirectional converter.

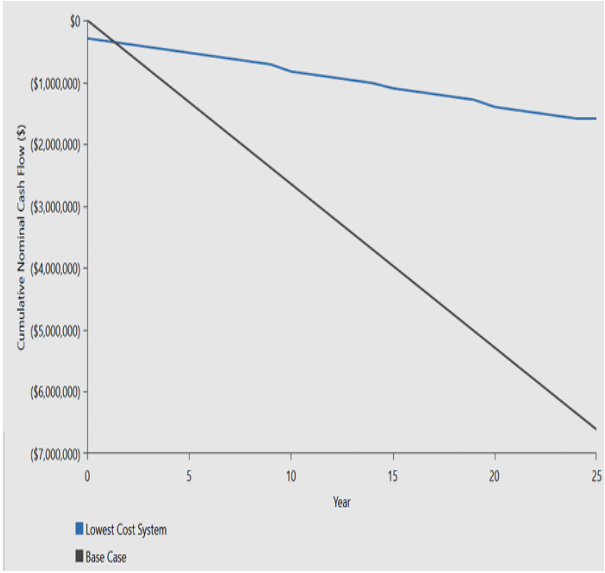


Figure 5: Best optimized system vs base case for the optimal hybrid system

Figure 5 compares the cumulative nominal cash flow of the optimal hybrid system with that of the existing base-case energy supply over the project lifetime. Both systems require an initial capital investment however; their long-term economic performances differ. The cumulative cost of the base-case system increases almost linearly throughout the analysis period reaching approximately 6.6 million USD after 25 years. This steady increase reflects the continued dependence on grid electricity and diesel generation both of which incur substantial recurring fuel, electricity purchase and maintenance costs. However, the cumulative cash flow of the optimal hybrid system increases much more gradually with the total lifecycle cost remaining below 1.7 million USD at the end of the project period. The large divergence between the two curves demonstrates the substantial economic benefit associated with integrating renewable energy into the existing energy supply infrastructure.

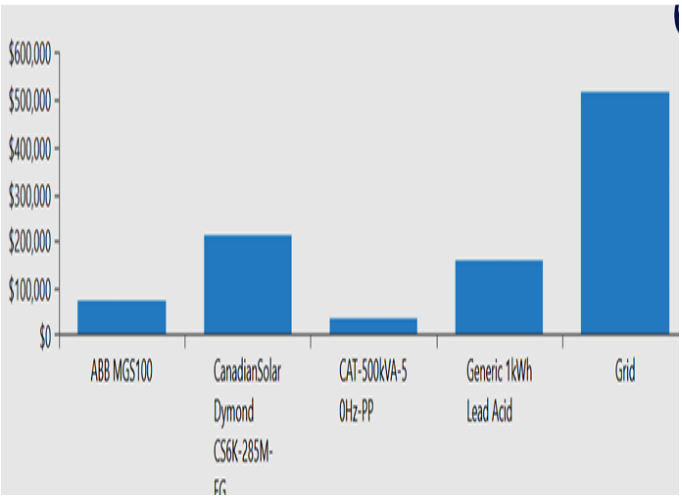


Figure 6: Net present cost by component of the optimal hybrid system

The observed reduction in lifecycle cost can be attributed to the contribution of photovoltaic generation which offsets a considerable proportion of energy purchased from the utility grid and reduces the operating hours of the diesel generator (Mulenga et al., 2023). Furthermore, the hybrid system requires a higher initial capital investment than conventional energy supply. The reduction in recurring operational expenses enables the additional investment to be recovered over the system lifetime. This finding agrees with Mulenga et al., (2023), which have consistently shown that grid-connected PV-based hybrid systems achieve lower lifecycle costs than conventional diesel-dominated electricity systems because of reduced fuel consumption and lower operating and maintenance requirements. Additionally, the distribution of net present cost among the major system components is presented in Figure 6. The utility grid accounts for the largest share of the total lifecycle cost indicates that energy purchases remain the dominant expenditure over the project lifetime despite the integration of renewable energy. Among the installed components, the photovoltaic array represents the highest capital investment, followed by the lead-acid battery storage system and the bidirectional converter, while the diesel generator contributes the smallest proportion of the total net present cost. The relatively high investment associated with the PV system reflects its role as the principal renewable energy source within the hybrid configuration. Similarly, the comparatively lower lifecycle cost of the diesel generator indicates that it operates primarily as a supplementary power source during periods of insufficient solar generation or high electricity demand rather than serving as the primary electricity producer (Kaygusuz, 2012).

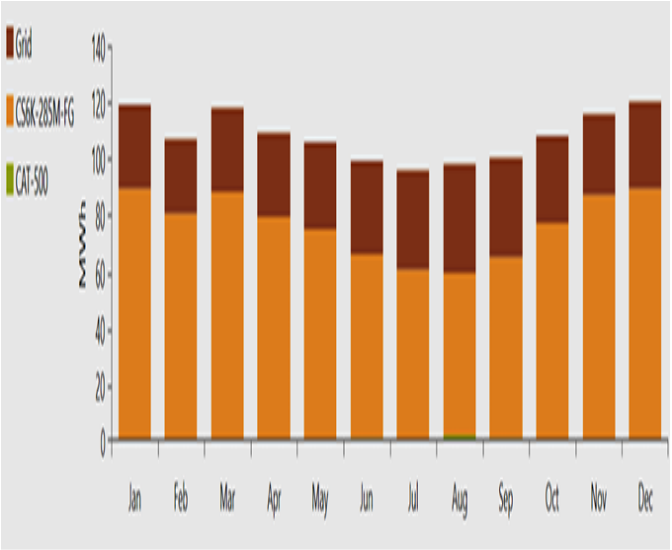


Figure 7: Monthly energy production of the optimal hybrid system.

The monthly energy production of the optimal hybrid system is shown in Figure 7. The results show that photovoltaic generation provides the dominant share of the monthly electricity supply throughout the year. However, energy obtained from the utility grid supplements the demand whenever solar generation is insufficient. Only a negligible contribution is observed from the diesel generator confirming that generator operation is limited to backup and reliability support. Furthermore, the result shows that the monthly energy production varies moderately over the year with slightly lower generation occurring during the mid-year months.

3.3 Operational Performance of the Optimal Hybrid Energy System

The operational performance of the optimal hybrid energy system was evaluated using the hourly simulation outputs generated by HOMER Pro. Figure 8 to 13 presents the annual operating behaviour of the major system components.

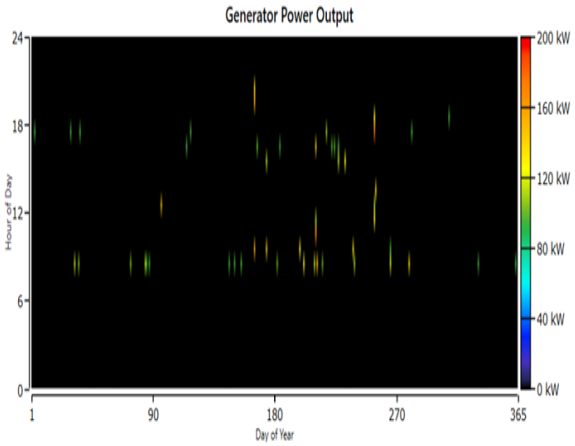


Figure 8: Annual CAT 500 generator power output for optimal hybrid system

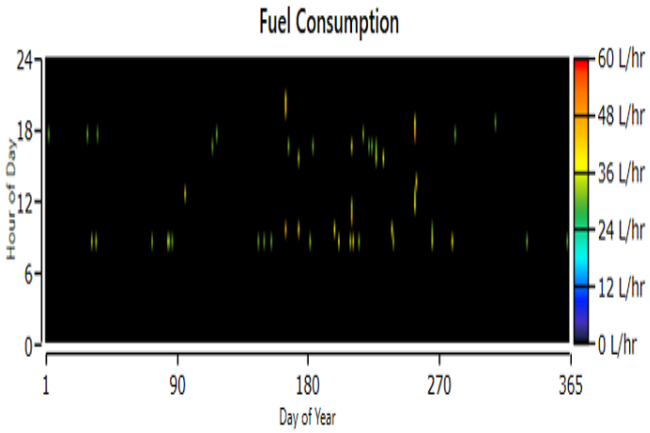


Figure 9: Annual CAT 500 generator fuel consumption for optimal hybrid system

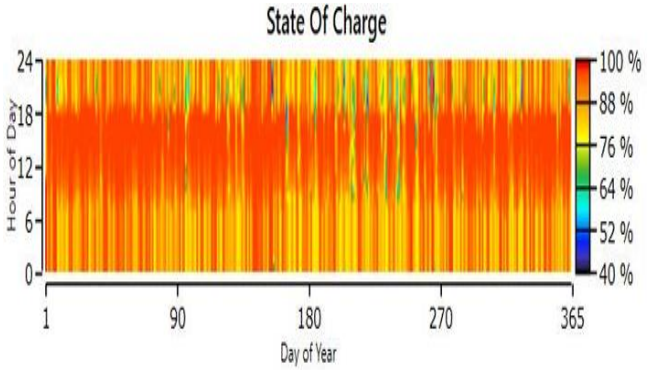


Figure 10: Battery state of charge for optimal hybrid system

Figure 8 shows the annual operating schedule of the CAT-500 diesel generator. The generator remained inactive for most hours of the year with operation occurring only intermittently when the available photovoltaic generation and battery storage were insufficient to satisfy the building's energy demand. Generator operation was concentrated within a relatively small number of days and occurred for short durations with output generally remaining below 200 kW. The fuel consumption closely follows the generator operating schedule (see Figure 9). This confirms that diesel is consumed only during periods when additional generation is required to maintain supply reliability. The maximum hourly fuel consumption remains below approximately 60 L h^{-1} while no fuel is consumed during the vast majority of operating hours. The sparse distribution of fuel consumption events throughout the year indicates that photovoltaic generation, battery storage and utility grid support successfully satisfy most of the building's energy demand without requiring continuous diesel operation. This operational strategy substantially lowers fuel expenditure and contributes to reduced greenhouse gas emissions compared with conventional diesel-dependent power systems. Furthermore, the annual battery state-of-charge (SOC) profile shown in Figure 10 shows the effective utilisation of the battery energy storage system. The battery remains predominantly within the 80–100% state-of-charge range throughout the year, with only occasional reductions below this level during periods of

prolonged high electricity demand or reduced renewable energy generation. The consistently high SOC indicates that excess photovoltaic energy generated during daylight hours is effectively stored for subsequent use thereby reducing reliance on the diesel generator and minimizing energy purchases from the utility grid (Issa et al., 2019). Furthermore, maintaining the battery within a high state-of-charge range is advantageous for lead-acid battery technology, as it limits deep discharge cycles that accelerate battery degradation and shorten service life.

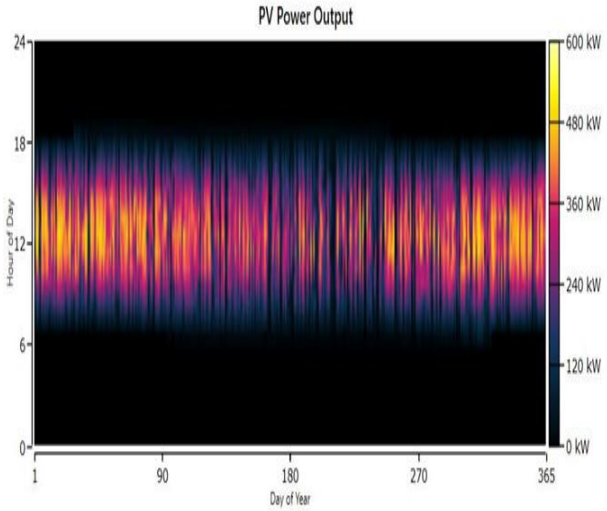


Figure 11: Annual Canadian Solar (PV) power output for optimal hybrid system

Figure 11 presents the annual power output of the photovoltaic array. As expected, electricity generation occurs exclusively during daylight hours, with maximum output observed between approximately 09:00 h and 15:00 h corresponding to periods of highest solar irradiance. Daily photovoltaic generation remains relatively consistent throughout the year, although moderate seasonal variations are evident due to changes in solar radiation intensity and atmospheric conditions. Peak power production approaches 600 kW demonstrating the substantial contribution of solar energy to the building's energy supply. Importantly, the periods of highest photovoltaic generation closely coincide with the daytime peak energy demand identified in Section 3.1. This allows for a significant proportion of the building load to be supplied directly by renewable energy. This temporal alignment between energy demand and solar resource availability represents one of the principal factors contributing to the favourable techno-economic performance of the hybrid system.

The interaction between the hybrid system and the utility grid is illustrated in Figure 12. energy purchases from the grid occur throughout the year, with demand varying according to the balance between building load, photovoltaic generation, and battery availability. Grid imports are generally highest outside the peak solar generation period particularly during early morning and evening hours when photovoltaic output is unavailable or insufficient (Pérez et al., 2024). Similarly, energy exported to the utility grid remains extremely limited with exported power rarely exceeding 0.03 kW. This shows that nearly all energy generated by the photovoltaic system is consumed internally by the

ECN building demonstrating a high level of self-consumption. The minimal energy export suggests that the hybrid system was appropriately sized to satisfy the building's demand rather than maximize electricity sales to the grid thereby improving the economic utilisation of the installed photovoltaic capacity.

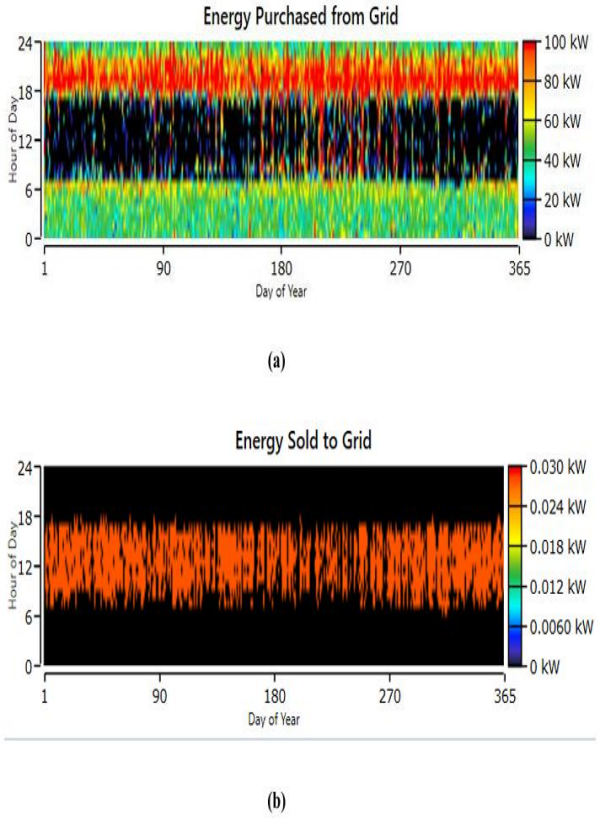


Figure 12: Energy (a) Purchased from grid, (b) Generated power output of optimal hybrid system.

The annual inverter power output is presented in Figure 13. The inverter exhibits continuous operation throughout the year with output varying in response to fluctuations in photovoltaic generation and battery charging and discharging activities. Peak inverter output approaches 200 kW reflecting its essential role in converting direct current generated by the photovoltaic array and battery bank into alternating current suitable for the building's electrical loads. The stable and continuous inverter operation demonstrates the effectiveness of the power conversion stage in coordinating energy exchange between the renewable generation system, battery storage, utility grid and connected energy demand.

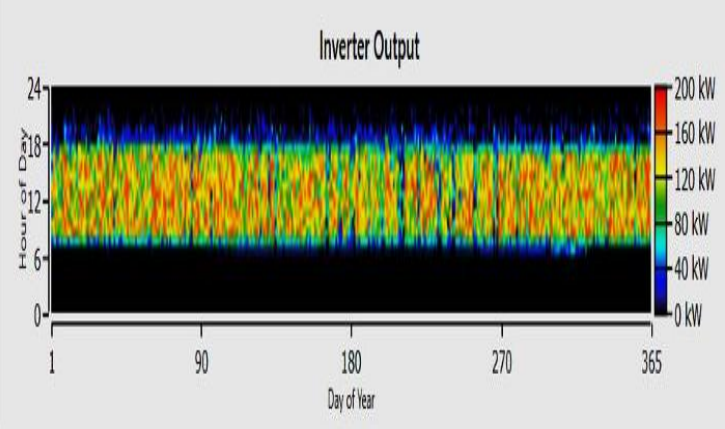


Figure 13: Annual inverter power output for optimal hybrid system

4.0 CONCLUSION

This study evaluated the energy demand characteristics and techno-economic performance of a renewable hybrid energy system for an institutional facility using measured load data and HOMER Pro simulation. The energy audit showed an average electrical demand of approximately 632.2 kW with a peak demand of 987.4 kW and an estimated annual energy consumption of approximately 5.54 GWh. Air-conditioning was identified as the dominant energy consumer while the load profile showed a strong daytime demand pattern that closely coincided with solar availability. The techno-economic assessment identified the PV–battery–diesel–grid configuration as the most favourable system. PV generation supplied the dominant share of energy while the battery provided energy storage. The diesel generator operated mainly as a backup source. The lifecycle economic assessment further showed a substantial cost advantage for the hybrid system compared with the base-case arrangement. The cumulative cost of the hybrid system remained at approximately US$1.7 million after 25 years compared with about US$6.6 million for the base case. These findings showed that integrating photovoltaic generation and battery storage with existing grid and diesel infrastructure can significantly improve the economic and operational performance of energy supply to institutional facilities.

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