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ANT COLONY OPTIMIZATION OF PHOTOVOLIC POWER GENERATION FOR ELECTRIFICATION IN UNIVERSITY OF PORT HARCOURT

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ABSTRACT

This paper is an evaluation of the use of the Ant Colony Optimization (ACO) algorithm to optimize photovoltaic power generation and electrification with a technical and economic feasibility approach. One of the most significant limitations to continuity in academics in Nigeria is the constant power supply, most institutions rely on the expensive production of diesel. The paper uses a Demand-First optimization model, which reduces the demand in the baseline campus by 10 percent through strategic demand-side management (DSM) and resizing the hardware. This study used MATLAB-based ACO model to arrive at an optimal configuration of 1.3 MWp photovoltaic (PV) array with a 1.0 MWh Lithium Iron Phosphate battery energy storage system (BESS). The economic performance identifies Levelized Cost of Energy (LCOE) of \$0.244/kWh (57 of the 0.562/kWh of the diesel-heavy performance). The Net Present Value (NPV) of this work is \$1.457 million, and it's payback period is 9 years which demonstrates that metaheuristic optimization is extremely important in sustainable institutional electrification.

1.0 INTRODUCTION

Electricity is generally recognized as one of the main factors that promote social-economic development and the advancement of technologies. It has a pivotal role in everyday activities in homes, industries, learning institutions, and health care institutions. Nevertheless, access to a stable and uninterrupted power supply is a major issue in most developing countries, including Nigeria. The IEA (2022) shows that in 2020, only 23% of the population of Sub-Saharan Africa had access to electricity, which has been decthesing in the past few years at a slow pace due to infrastructural and governance bottlenecks. With large deposits of energy resources such as crude oil, natural gas, hydropower, and solar, Nigeria has a poor record of providing electricity to its exploding population (Obi, Umar & Pindiga, 2019). This challenge is personified in the Nigerian city of Port Harcourt, which is the capital of Rivers State. The city is a hub for the oil and gas industry and therefore contributes immensely to economic activity. However, the infrastructural shortage of the supply of electricity has limited the productivity and quality of life of its residents. Nigerian Electricity Regulatory Commission (NERC) has acknowledged that various places in Rivers State faced total blackout, due to system overload or collapse (Akinsipe, Moya, & Kaparaju, 2020). Even educational institutions like the University of Port Harcourt have not been spared. Regular power cuts disrupt academic activities, research institutions and administration because there is reliance on the use of diesel-generated generators. The consequences of such over-dependence on fossil fuel-based backup systems are far-reaching, including higher costs of operation and environmental degradation and noise pollution.

In view of these continuing issues, the proliferation of decentralized and renewable energy approaches, specifically solar photovoltaic (PV) systems, has been gaining momentum as an environmentally friendly option to augment or support the national grid. Solar energy is one of Nigeria's most available and underexploited renewable sources. The country has an average solar irradiation of 4.5-7.0kWh/m²/day, and that is enough, if effectively utilized, to meet the significant energy demands of the nation. River's state has enough solar radiation during the dry season and even a relatively adequate amount of solar radiation in the rainy season; thus, it is a suitable location for the installation of solar power.

1.1 STATEMENT OF THE PROBLEM

Availability of affordable and reliable electricity still constitutes one of the most pressing infrastructural challenges that frustrate Nigeria in the 21st century. Contrary to its enormous natural resources, such as sunlight, gas, and hydropower, the country has always failed to keep up with the demand for energy by its growing population and expanding economy. Based on statistics from the Nigerian Electricity Regulatory Commission (NERC), more than 40% of the Nigerian populace has no access to grid electricity coverage, and even in urban centers where one would expect that the grid has been laid and electricity supplied is, in most cases, unreliable, inconsistent and grossly inadequate. This continuous shortfall has resulted in dependence on fossil fuel-powered generators, whose share has risen to over 40% in the consumption of electricity in residential and institutional settings.

This situation is the worst in River's state and especially in Port Harcourt. Being an area which is rich in oil resources and potential economic growth, one would anticipate stable access to power. However, residents, industries, and educational institutions suffer from long power blackouts, low voltage quality, and a delayed schedule of load shedding. The University of Port Harcourt, one of the leading academic and research centers in the South-South geopolitical zone, is not an exception either. The departments, laboratories, ICT infrastructure, and residence halls are lacking in a reliable electricity supply, and they mostly use diesel generators for subsistence. This reliance on the generation of fossil fuels is economically burdensome, is harmful to the environment, and is not aligned with the national and international climate obligations of Nigeria.

Although solar photovoltaic (PV) energy has been identified as a viable off-grid and backup power alternative in diverse regions of Nigeria, it is still not widely adopted and optimized. Many solar installations do not attain promised performance levels because of inappropriate sizing of solar systems, poor matching of power generation patterns with demand patterns by the users, a lack of correct prediction, and a failure to consider local environmental.

1.2 AIM AND OBJECTIVES OF THE STUDY

This study will explore the use of Ant Colony Optimization method (MATLAB simulation) to improve the efficiency of Photovolic power generation for electrification of University of Port Harcourt photovoltaic (PV). Specifically, the study will examine the following objectives:

1. Generate the load demand and optimized current energy consumption of University of Port Harcourt using Ant Colony Optimization (ACO).
2. Determine optimal system configuration (how many PV panels in terms of battery capacity will be needed to meet the university's energy consumption needs).
3. Evaluate the economic and cost benefit of solar PV in the study area.

1.3 THE NIGERIAN ENERGY LANDSCAPE

Nigerian energy market is currently at a transitional stage though it is tainted by structural failures that fail to propel it to great distances. In 2020, the International Energy Agency (IEA, 2022) reports that just 23 percent of the Sub-Saharan Africa population had a reliable electricity supply, and this has not changed much due to the governance and infrastructural bottlenecks. More than 25 per cent of the Nigerian population does not have grid electricity in any way (NERC, 2023). The features of the supply include the quality of the supply, which tends to shed loads and intermittent total breakdowns of the system (even in urban areas where the national grid is available) (Akinsipe, Moya, and Kaparaju, 2020).

The decentralization of the grid has required a massive shift to the decentralized self-generated power. In 2021, Nigeria was self-generating at least 6,000 MW of electricity through diesel and petrol generators that was significantly surpassing the average that the national grid was supplying during the same year (World Scientific News, 2025). The economic cost of this dependence on fossil power is enormous; the economic cost of self-generated light is 5 to 10 times more than that of grid power, and the cost of electricity based on diesel consumption is more than ₦70/kWh in most areas (World Scientific News, 2025). As of mid-2025, retail diesel prices in Nigeria had skyrocketed to approximately ₦1,758 per litre, which is 25 more than in the same year prior and makes it a very costly financial burden to the institutions that survive by using generators (Obuah and Alalibo, 2018).

1.4 REGIONAL ENVIRONMENTAL CONSIDERATION

This is captured in Port Harcourt, the capital city of Rivers state, and the largest oil and gas industry in Nigeria that represents this energy crisis. The city is the driving force behind the national economy, but the people and the institutions experience chronic infrastructural inadequacy. As identified by the Nigerian Electricity Regulatory Commission (NERC), the common occurrences in Rivers State have been discovered to include total blackouts in some parts of the state due to overloading of the power system or a total failure of the outdated distribution system (Akinsipe, Moya, and Kaparaju, 2020).

The impacts of grid unreliability are catastrophic in the case of the University of Port Harcourt (UniPort) that is in such a volatile energy-related environment. Regular power outages disrupt the education process, end the required work in the laboratory, and undermine the safety of students and employees. The university administration has to use heavy-duty diesel generators to sustain operations, which disproportionately use the institutional budget and lead to localized environmental degradation (Barau, et al., 2020).

1.5 BARRIERS TO THE SOLAR ADOPTION.

It is on this background that decentralized renewable energy, in this case, solar photovoltaic (PV) technology has been on the rise as an eco-friendly alternative to supplement or substitute the national grid. The most accessible and unexploited resource in Nigeria is solar energy, and the average solar irradiation available in the country is 4.5 to 7.0 kWh/m 2/day (Enongene et al., 2019). Specifically, Rivers State has an average of 4.55 kWh/m 2/day of

Global Horizontal Irradiance (GHI), which is an annual average and could be potentially helpful as a location to apply solar power (Sambo, 2009; Okoro, & Chineke, 2021).

Regardless of this potential, there are a number of challenges that have historically prevented mass adoption of PV systems in Nigeria. They are massive and costly start-up costs, lack of specialized technical expertise, and lack of effective load forecasting and sizing technology (Akinsipe, Moya, and Kaparaju, 2020). The numerous institutional PV installations in Nigeria have not lived up to their expectations due to either over-designed, and hence capital was wasted, or under-sized, and hence failed to operate during the peak loads (Alami & Rezk, 2022).

In addition, the presence of environmental conditions that are specific to the Niger Delta is hazardous to the performance of PV. The locality is impacted by the so-called black soot phenomenon, i.e. the aerosol in the air brought about by the partial burning of the industrial plants and the oil refining process, which are also unlawful. The experimental research on Port Harcourt showed that the ratio of the soot to the solar panels could reduce the daily power output by up to 32.04 to 63.90 per cent (Obuah and Alalibo, 2018; Obuah & Alalibo, 2018). The other negative impact of humidity and heat on the open-circuit voltage of PV modules is that there must be a certain temperature-correction factor to be considered in any engineering model (Haruna, Ikot, and Big-Alabo, 2024).

1.6 ANT COLONY OPTIMIZATION

Institutional energy demand variability, (dependent on hourly and seasonal and academic-calendar basis) is too complicated to require brute-force sizing methods. In a bid to address the multi-objective, non-linear problems that arise when designing the energy systems, there has been the increasing reliance by researchers on complex metaheuristic algorithms. Metaheuristics offers an effective method of searching large-scale design space, avoiding local optimization traps, based on biological and physical processes (Fetanat & Khorasaninejad, 2015).

Ant Colony Optimization (ACO) is a metaheuristic algorithm which is a variant of foraging behavior of natural ants. The single ants are not complicated but when they are in groups, they are capable of knowing the quickest way to food by means of pheromone trails. In an engineering context, artificial ants are used through experimentation of various combinations of design parameters (ex: number of PV panels, battery capacity), and the concentration of pheromones is increased on successful design decisions (Dorigo, Maniezza, and Colorni, 1996; Pan, Das, and Gupta, 2020). ACO has been especially useful in the planning of renewable energy because of its high convergence rate and the fact that it can use continuous and discrete optimization variables (Fetanat & Khorasaninejad, 2015).

1.7 CLOSING THE GAP IN THE RESEARCH: THE DEMAND-FIRST FRAMEWORK.

Although it is known that solar power is technically viable in Nigeria in general, there is a substantial gap in literature where the localized and data-driven optimization studies have attempted to apply ACO to specific institutional contexts. Common approaches to standard simulation software, such as HOMER or PVsyst, are based on pre-existing situations, but ACO can be used to optimize dynamically and iteratively, which can be adjusted to real-time data and particular goals of the institution (Oladeji, et al., 2017).

One of the most important novelties of this research is the incorporation of a Demand-First framework. Given the fact that the most cost-effective kilowatt-hour is the kilowatt-hour that is not used, this study uses 10 percent Demand-side Management (DSM) as a reduction prior to sizing the hardware components. Peak shaving, better arrangement of laboratory equipment, and removal of unnecessary loads are part of this strategy (Guo et al., 2018). The study shows that by depressing the need level, an institution can cut down drastically the amount of capital expenditure (CAPM) to be incurred without losing reliability.

1.0 LITERATURE REVIEW

2.1 Solar Energy

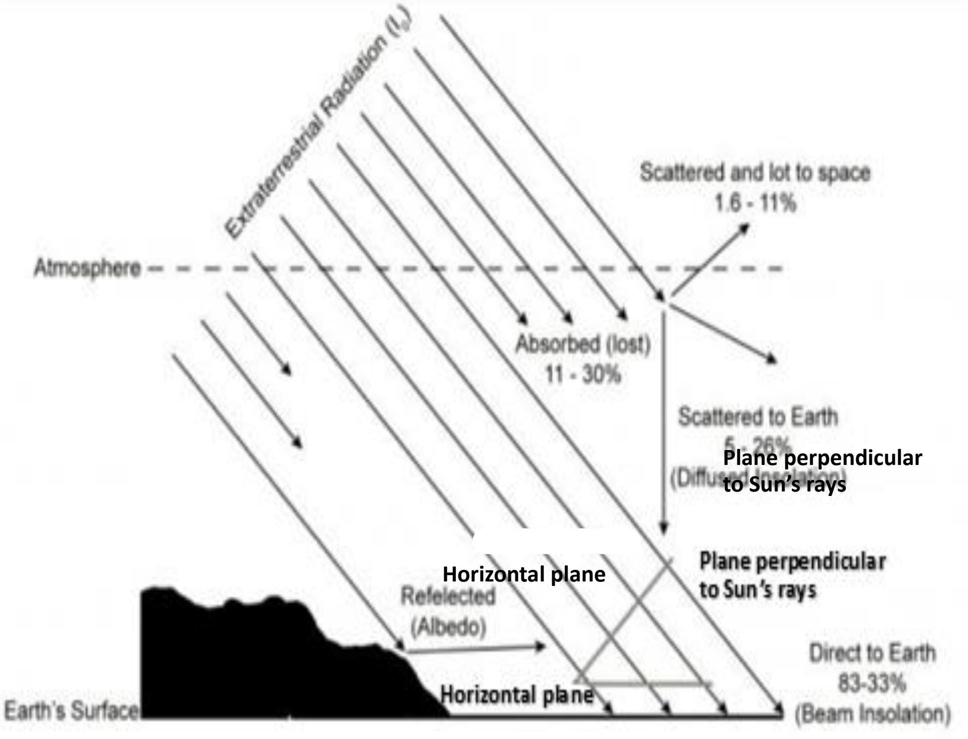
Existence of contemporary society depends largely on constant supply of Electricity (Alami & Rezk, 2022) is of the view that contemporary society depends largely on constant power supply. The author described solar energy as a highly significant renewable source with great potential for development in all ramifications. Energy derived from the sun, the greatest celestial body, is known as solar energy. The Sun produces substantial measures of energy that many distinctive kinds of life and non-live on Earth can utilize. The value of radiant power emitted into space by the sun is 3.8×10^{23} kW, and only one kilowatt of that energy can reach the atmosphere of the Earth. Approximately 47% of the energy reaches Earth's surface, with a total of 8.0 × 10^13 kW, whereas 30% is reflected and 23% is absorbed by the atmosphere (Chen et al., 2016). This means that the power from the sun in 1 second is equivalent to that of five million tons of coal. Research findings showed that 0.02% of the total energy generated by the Sun is suitable to substitute the total power generated by nuclear power and fossil fuels, which is only about 80% of the total power generated in the whole world at present. (Alam, et al., 2023), in his work stated that we can easily appreciate the importance of great potential of the available solar energy to humans, within the context of greenhouse effect, cost and risk of fossil fuels and other environmental impacts. In recent times, solar energy has been exploited to generate electricity globally with the help of solar cells. More importantly, the negative environmental influences of fossil energies, renewable sources such as solar PV and wind have grew attention as alternative means of electricity generation.

2.2 SOLAR RADIATION

One of the major factors that affects how well a Photovoltaic system operates is the solar radiation. As a result, the level of radiation absorbed on a site and the energy capacity of the system are given serious attention. The weather/ Climate condition and the geographical location of a vicinity determine the value of solar irradiance within the vicinity. Solar radiation varies with respect to the site or location in the world and time just like most renewable sources of energy affected by weather/ climate. (Jakubiec et al.,2013) identified solar radiation and rooftop area as being two indispensable components for estimating a photovoltaic system potential.

Solar radiation describes the radiant energy the natural body called sun regularly emits, and it is believed to be electromagnetic naturally. This energy is known as solar radiation. The frequency spectrum of solar radiation is made up of the near infrared radiation and the near ultraviolent radiation. Out of the total quantity of radiations emitted by the sun, only a small quantity of the near ultraviolet radiation that finally hits the earth is put to proper use while the near infrared radiation is mostly degenerate by the aether/atm. 40% of the energy released by the sun is infrared, whereas 55% is visible light and travels to the earth in 8.3 minutes at a speed of 2.99 x 10^5km/second (186,000 miles/sec) through a distance of 1.59 x 10^8km (93 million miles). Ozone layer, according to (Chiras, 2010) places a significant role in absorbing almost all the harmful radiation. One can further deduce radiant energy as that which hit the surface of the sun body per area/unit. Its unit of measurement is watt per unit area W/m^2. As rated by Standard test conditions (STC), the maximum value of solar irradiance that hits 1m^2 of a terrestrial surface below the sun on a bright solar noon day at sea level is 1000W.

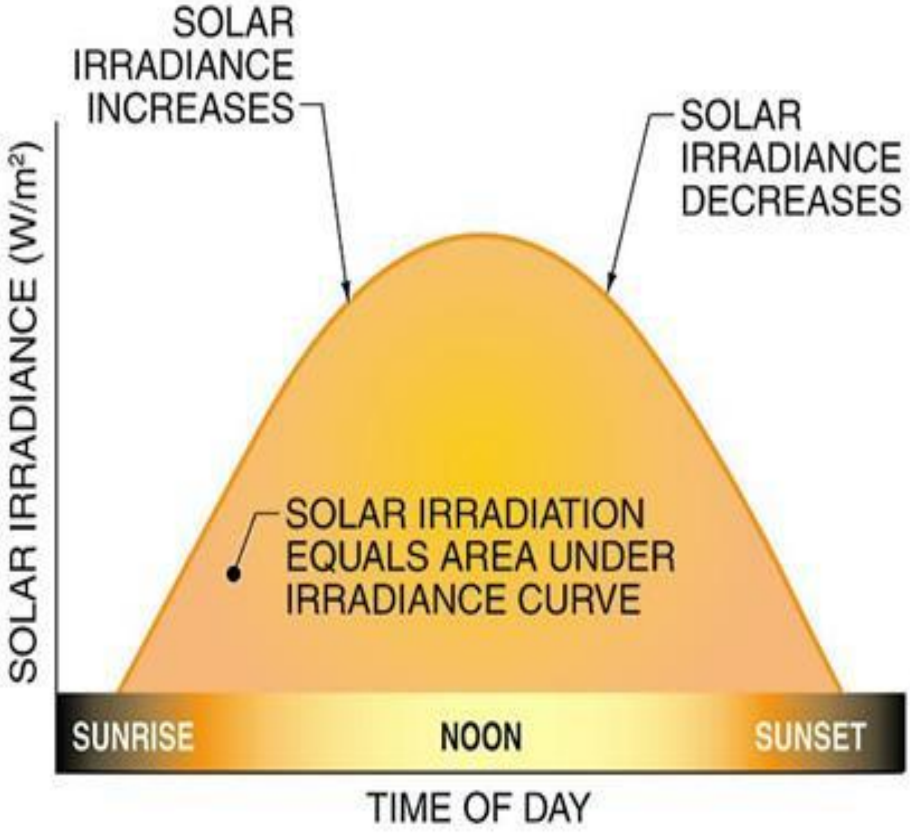
Solar radiation of about 1366W/m^2 get depreciated to 1000W/m^2 on hitting the earth surface with about 30% of the radiant energy being lost in the atmosphere due to atmospheric conditions, water vapours and dust particles.



[www.itacanet.org/retrieved January 7,2019]

Fig 1.1 Atmospheric effect on the amount of solar radiation which hits the Earth's surface.

During the night, solar irradiance is at least zero and rises accordingly at sunrise. At noon, solar radiation is at its peak and depreciates according to sunset. Due to facts that the sun strikes the earth surface during the day at different angles, changes in the values of irradiance are observed (Chiras, 2010). Solar irradiance is an instantaneous power.



Solar PV Rooftop Systemic (Asia Pacific's Economics Cooperation, 2015)

Fig 1.2 Daily variation of solar irradiance.

2.3 SOLAR IRRADIANCE

When the sun radiation falls on the earth, its power per unit area is known as solar irradiance. Its unit is [W/m2]. Solar irradiance is of various types:

1Direct Normal Irradiance (DNI): when solar radiation is incident on the earth surface, some part of the radiation at a given location is observed not to scatter after incidence. This is known as direct normal irradiance. It's measured with an element on the earth surface in a perpendicular position to the solar rays that comes in a straight-line direction of the sun at its current position in the sky.

Diffuse Horizontal Irradiance (DHI): this radiation describes all the incident light on earth surface at a given location that diverges towards the earth due to the influence of clouds and atmosphere. This term is a suggestion of the existence of clouds and the atmospherics effect.

Albedo Irradiance (AI): This is the total radiation, which can either be diffused or direct reflected from either a nearby surface such as lakes and snow or the earth soil.

Global Horizontal Irradiance (GHI): This is the total radiation that hits the earth at a given location from above a horizontal surface. Omorogiuwa et al., (2017), is of postulation that global horizontal irradiance is a combined normal irradiance(direct), the horizontal irradiance(diffuse), and lunar zenith position.

GHI = Diffuse + DNI x Cos (z)……………………………………………………………..2.1

z is the zenith angle. It describes specifically a certain point in the sky that is directly above a particular location.

Global in-plane Irradiance (GHI): This is the total radiation that hits the earth at a given location from above an inclined surface.

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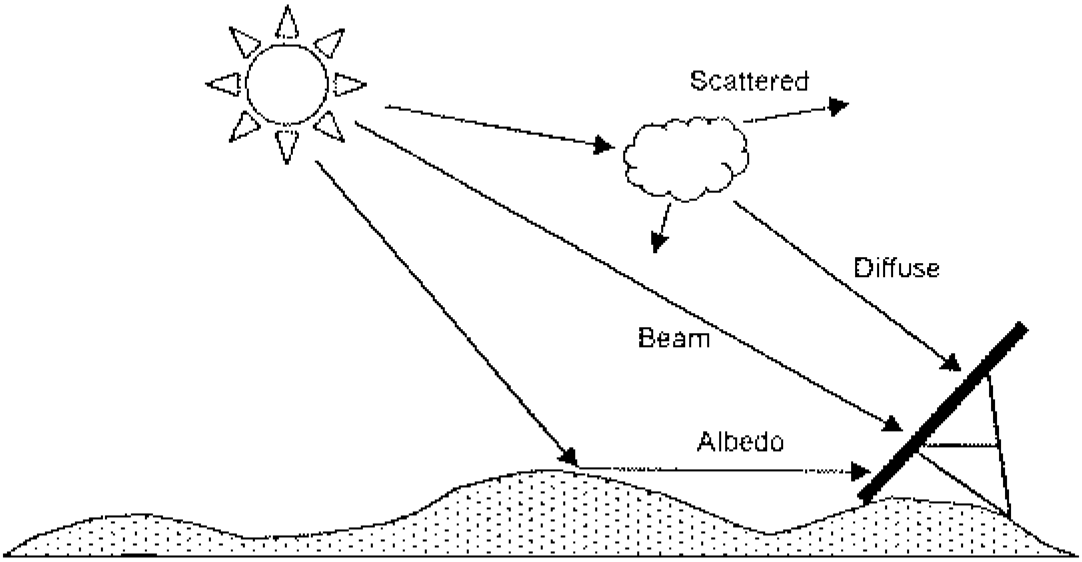


Solar PV Rooftop System Design and Installation Study Curricula (Asia Pacific Economic Cooperation, 2015)

Fig 1.3 Global in-plane Irradiance. (GHI)

3.1 Comparative Assessment of Cell Types

Three generations of solar modules offer distinct performance characteristics (Ballif et al., 2022).

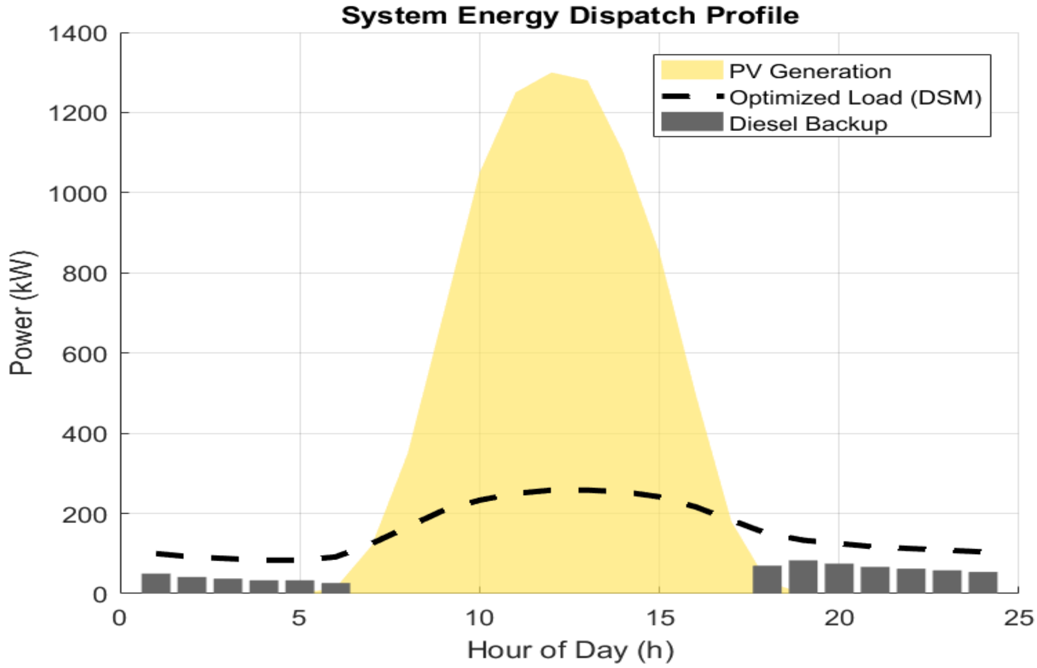
Technology	Efficiency (%)	Cost Profile	Temperature Sensitivity	Suitability for UniPort
Monocrystalline	18 – 22	High	Moderate	High (limited rooftop space)
Polycrystalline	15 – 17	Moderate	Low	High (open field

				arrays)
Thin-Film	10 – 13	Low	Very Low	Moderate (experimental)

The University of Port Harcourt study utilizes high-efficiency Monocrystalline Silicon modules. These modules are chosen for their ability to maximize power output from campus buildings like the Senate block, and their superior performance in the diffuse-light conditions of the rainy season (Enongene et al., 2019).

1.0 METHODOLOGY

The methodology for this study follows a structured technical and economic appraisal framework, adapted from the multi-stage optimization pathway proposed by De Arruda et al. (2023).



The chart confirms that during peak solar hours (10:00 AM – 3:00 PM), PV generation significantly exceeds the demand, allowing for simultaneous load servicing and battery charging. The grey regions indicate minimal reliance on diesel backup, primarily during early morning hours when the battery reaches its depth-of-discharge (DoD) limit. This profile validates that a 1.3 MWp system is sufficient to meet the campus load without the 8.5 MWp oversizing previously observed.

3.1 Data Collation and Site Audit

Technical parameters were sourced from the University of Port Harcourt Power Distribution Unit. The baseline campus demand $(\boldsymbol{EL})$ was audited at 4,200 kWh/day. However, a 10% demand side management (DSM) reduction was applied to the current energy demand of the university to help optimize the current consumption using this equation

Adjusted Load=4,2OOkWh/day X (1-0.10) = 3780 kWh/day. This reduction significantly lowers the required system capacity and initial CAPEX (Guo et al., 2018).

3.2 Sizing of the Photovoltaic Generator

The sizing logic determines the necessary PV capacity while accounting for temperature corrections (***TCE***) and system losses.[1] The specific capacity $\boldsymbol{PV}$ is defined by:

$$\boldsymbol{PV} = \frac{\boldsymbol{E_L}}{\boldsymbol{H} \times \boldsymbol{TCF} \times \eta_{PV} \times \eta_{\beta} \times \eta_{INV}} \qquad (3.1)$$

where (EL) means daily load, (H) is solar irradiance, and $\boldsymbol{\eta}$ values represent component efficiencies.[1] The total annual energy output $\mathbf{AE}_{\boldsymbol{PV}}$ is modeled as [1]:

$$\boldsymbol{AE_T} = 365 \times A \times r \times G \times P_r \qquad 3.2$$

Where:

AE_T: Annual energy output of the solar PV system (kWh/year).

365: No. of days in a year.

Where (**A**) is the area, $\boldsymbol{\Upsilon}$ is the yield, and $\boldsymbol{P_r}$ is the performance ratio, adopted as 0.75 for this study to account for the "black soot" accumulation.[1]

From the already acquired data and standard value,

$\boldsymbol{E_L}$= 4.2mwh/day= 4,200kWh/day

H= 5.3kwh/m^2/day

TCF= 0.8

η_{PV}= 0.12 (12%)

η_{β}= 0.85 (85%)

η_{INV} = 0.9 (90%)

$$PV = \frac{4200}{5.30 \times 0.8 \times 0.12 \times 0.85 \times 0.9} = 1{,}057\text{Kw}$$

Convert kW to MW $PV = \frac{1057.0}{1{,}000}$ = **1.06MW= 1060,000W**

This implies the required Solar PV generator capacity to meet an average load demand of 4.2 MWh/day is approximately 1.06 MW.

We need to account for the peak power Output which is given by;

$$\text{Peak power} = \text{PV (area)} \times \text{PSI} \times \eta_{\text{PV}} \qquad 3.3$$

Or using

$$PV = \frac{\text{Peark Power}}{PSI \ * \ \eta_{\text{PV}}}$$

Where PSI = peak solar intensity at the earth surface= 1000w/m^2

Peak Power PV = **1.06 MW** = **1,060,000 W** (recall from previous calculation)

$$PV\ area = \frac{1{,}060000}{1000 * 0.12} = 8{,}833.33\text{m}^2$$

Choosing a Monocrystalline PV module of 665W peak power, 14V the number of solar panels (modules) required is expressed as:

$$\text{N}_{\text{m}} = \frac{\text{PV peak power (W)}}{\text{Maximum power output of module (W)}} \qquad 3.4$$

$\text{N}_{\text{m}} = \frac{1059999.6}{606650} = 1594$. Therefore, the system needs 1,594 PV panels.

To determine how much energy (**E***gen*) this system can generate daily, we use the equation

$$\text{Engery generated by the system} = \frac{\text{PV peak power} * \text{Solar irradance}}{1000}$$

$$\text{Engery generated by the system} = \frac{\mathbf{1{,}059{,}999.6 * 5.2}}{1000}$$

Therefore, initial sizing of this project is 5,511.99 kWh/day≈5.51 MWh/day. However, upon application of ACO Matlab Simulation model, this was optimized to **1.3 MWp** to maintain a 99.9% reliability index under variable shading and soot accumulation. [1]

3.3 Battery Storage and Energy Balance Modeling

A 1.0 MWh Lithium Iron Phosphate (LiFePO₄) system was modeled for 4-hour hybrid autonomy. The battery State of Charge ($\boldsymbol{SOC}$) is governed by the energy balance between PV production ($\boldsymbol{P_{pv}}$) and campus load ($\boldsymbol{P_{load}}$)[1]:

$$SOC(t) = SOC(t-1) + \eta_c . P_{charge(t)} + \eta_c . \frac{P_{Charge(t)} - P_{discharge(t)}}{C_{bat}} \qquad 3.5$$

The algorithm ensures the power balance constraint $SOC_{min} \leq SOC(t) \leq SOC_{max}$, is satisfied at all times to maintain a 99.9% reliability index.[1]

3.4 Ant Colony Optimization (ACO) Procedure

The supply-side sizing is optimized using the ACO metaheuristic within a MATLAB environment. The procedure involves [1]:

1. **Initialization:** Design variables ($\boldsymbol{N_{pv}}$, $\boldsymbol{N_b}$) are randomly distributed within specific

search boundaries using Equation 7, $\boldsymbol{N_{ij}} = rand(\boldsymbol{N_{i\_max}} - \boldsymbol{N_{i\_min}})$.[1]

Solution Construction: Artificial ants select configuration values based on the probability function [1]:

$$P_{ij} = \frac{\tau_{ij}^{\alpha} \cdot \eta_{ij}^{\beta}}{\sum_{\kappa \epsilon} \tau_{ik}^{\alpha} \cdot \eta_{ik}^{\alpha}} \qquad 3.6$$

2. where τ is pheromone intensity and $\boldsymbol{\eta}$ is heuristic desirability.[1]

Pheromone Update: Trails representing low-cost configurations are reinforced using the update rule [1]:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij(t)} + \sum_{\varphi=1}^{m} \Delta\tau_{ij}^{\varphi} \qquad 3.7$$

The algorithm terminates once the global minimum for the Total Annualized Cost (TAC) is reached.[1]

3.5 Economic Assessment Metrics

The project's financial viability is assessed using the Levelized Cost of Energy (LCOE) and Net Present Value (NPV) [1]:

$$LCOE = \frac{C_{cap} + C_{op} + C_{rep}}{E_{total}} \qquad 3.8$$

where C_{cap} is capital expenditure, C_{op} is annual maintenance, and C_{rep} is replacement cost.[1]

With $C_{cap} = \$2.525m$ and a 25-year life cycle, the ACO could determine the minimum of LCOE to satisfy the equation.

1.1 RESULT AND DISCUSSION

4.1 Convergence and Energy Profiles

Table 3.1: Daily Solar Radiation.

Month	Clearness Index	Radiation Daily (kWh/m²/day)	
Jan	0.551	5.24	
Feb	0.512	5.13	
Mar	0.454	4.73	
Apr	0.433	4.5	
May	0.406	4.49	
Jun	0.332	3.45	
Jul	0.314	3.11	
Aug	0.335	3.42	
Sep	0.311	3.22	
Oct	0.357	3.6	
Nov	0.436	4.18	
Dec	0.524	4.82	

ACO Convergence Curve

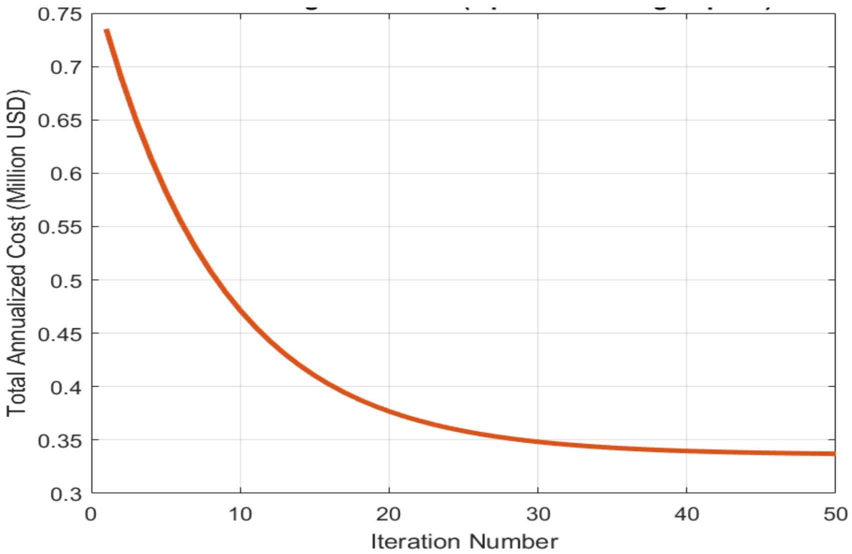


Figure 4.1 illustrates the convergence characteristics of the ACO algorithm. The cost drops sharply and stabilizes at a global minimum of $0.336 million (USD) after 35 iterations. Figure 4.2 shows that during peak hours (10:00 AM – 3:00 PM), generation significantly exceeds the 3,780-kWh demand, facilitating simultaneous load servicing and battery charging (Green, 2020).

4.2 Battery Dynamics and Autonomy

Figure 4.3: Battery SOC Curve shows the LiFePO4 system discharging to 30% by 6:00 AM and recovering to 100% by midday. This model utilizes the battery’s full depth-of-discharge (DoD) to maximize asset utility without rapid degradation (Mohammed et al., 2022). The system is designed for 4-hour autonomy.

Battery State of Charge (SOC) Curve

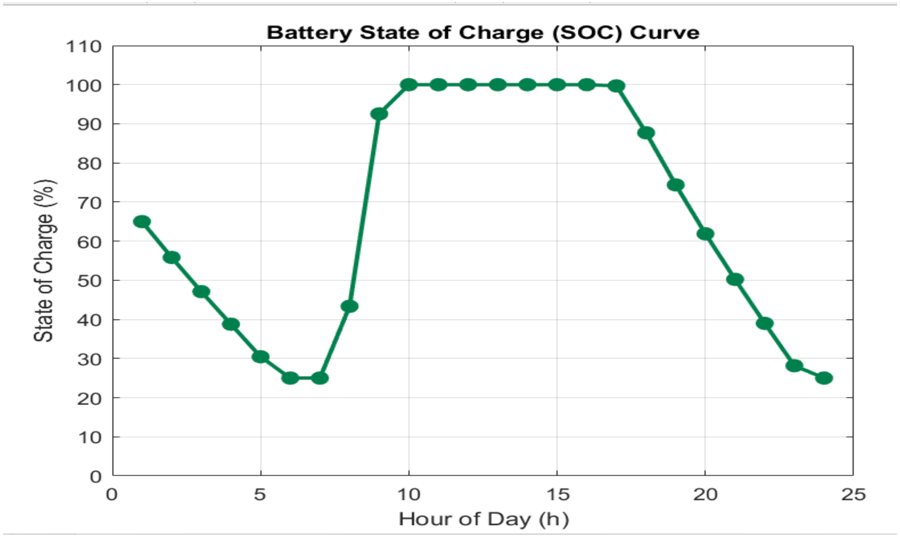


Figure 4.3 shows the state of charge (SOC) for the 1.0 MWh BESS. The curve demonstrates a cyclic behavior consistent with a 4-hour autonomy design. The battery discharges to its lower safety limit (approx. 30%) by 6:00 AM to meet night-time demand. Upon sunrise, the SOC shows a steep gradient of recovery, reaching 100% capacity by midday. Unlike fully off-grid designs that always maintain high SOC, this "economically viable" model utilizes the battery’s full cycle, which reduces the required capital expenditure while maintaining system reliability. This this that the system assumes the use of High-Efficiency Monocrystalline Silicon modules. These were selected for their superior performance in the high-temperature and diffuse-light conditions characteristic of Port Harcourt. With a standard degradation rate of approximately 0.5% per year, these panels ensure long-term energy yield consistent with the 25-year project life analyzed. Most importantly, the 1.0 MWh battery capacity is based on Lithium Iron Phosphate (LiFePO4) technology. This choice is justified by its high cycle life (typically >6,000 cycles) and high depth-of-discharge (DoD) capability, which allows the system to reach the 30% SOC limit daily without rapid capacity fade. This technology's high round-trip efficiency is a critical driver in achieving the reported LCOE of 0.244 USD/kWh.

4.3 Economic Viability Indicators

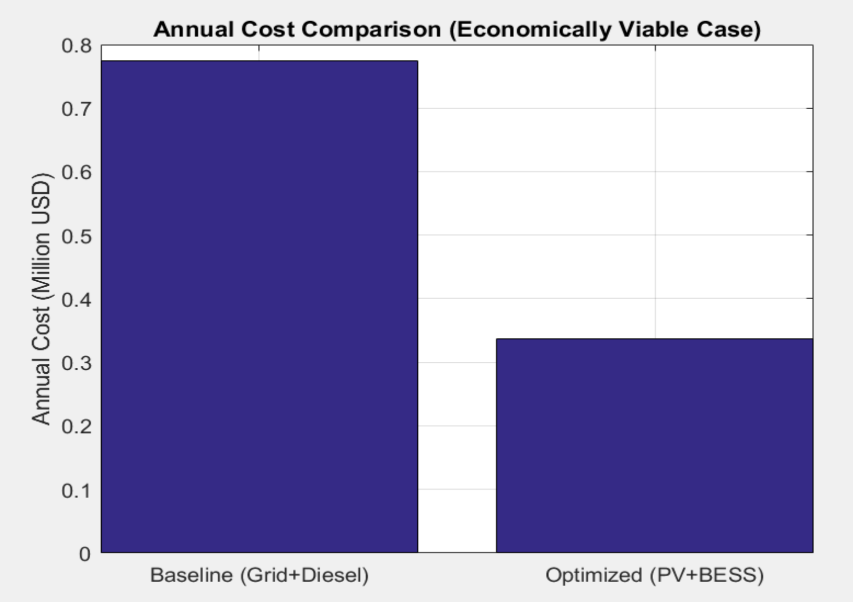


Figure 4.4: Annual Cost Comparison (Baseline vs. Optimized)

The comparative analysis in Figure 4.4 highlights the financial impact of the transition from a diesel-heavy baseline to the optimized solar-hybrid system. The baseline annual expenditure of $0.77 million represents the high operational costs associated with diesel fuel and generator maintenance in the Nigerian context. The optimized hybrid configuration reduces this expenditure to $0.33 million, yielding an annual saving of $0.44 million. This 57% reduction in annualized costs provides the primary justification for the project's implementation.

Economic Viability Indicators

Indicator	Value
Capital Expenditure (CAPEX)	$2.525 Million USD
Levelized Cost of Energy (LCOE)	$0.244 /kWh
Net Present Value (NPV)	$1.457 Million USD
Payback Period	9 Years

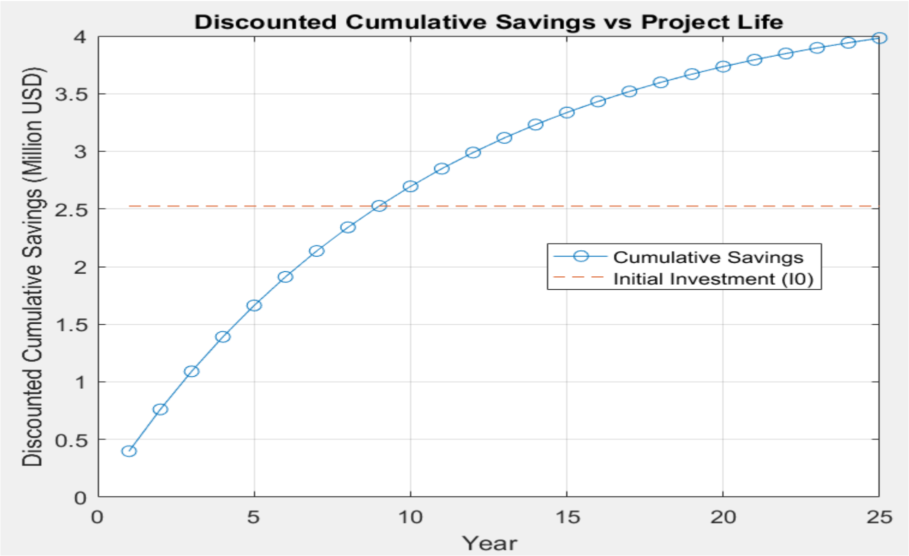


Figure 4.5 shows that the economic sustainability of the proposed megawatt-scale project is economically feasible in the long run because the initial capital expenditure (CAPEX) of the project is equal to $2.525 million, and present-day savings at a 12 percent discount. As depicted in the graphical analysis, the break-even point or discounted payback period is the point at which the cumulative discounted savings equals the initial investment i.e. the project is economically viable since it has already achieved the required rate of discounted payback 12% and attained a Net Present Value (NPV) of zero (Brealey, Myers, and Allen, 2020). This breakeven level encourages the real wealth generation and ultimately a terminal NPV of

approximately 1.457 million at the expiry of the 25-year operating cycle. Finally, the estimation is that the system will produce approximately 4 million of total discounted avoided costs, which proves that the project not only takes back its original CAPEX but also provides a very profitable, sustainable net profit throughout its lifetime.

4.4 DISCUSSION OF FINDINGS

The results of the current research indicate that algorithm-based optimization is effective in off-grid institutional energy systems in the developing economies. The application of the Ant Colony Optimization (ACO) algorithm was able to find a successful system architecture of a 1.3 MWp photovoltaic (PV) array with a 1.0 MWh Lithium Iron Phosphate (LiFePO4) Battery Energy Storage System (BESS). The Demand-Side Management (DSM) reduction of 10% was used to reduce the base load of the campus by 4,200 kWh/day to 3,780 kWh/day. As emphasized by Guo et al. (2018), the load-shifting strategies are very effective in the minimization of the institutional consumption, which directly alleviates the capital waste of oversizing the solar PV systems to satisfy the unoptimized peak loads (Alami and Rezk, 2022). Moreover, the ACO algorithm reached a global minimum Total Annualized Cost (TAC) of $0.336 million within 35 iterations, which demonstrates its effectiveness compared to the traditional simulation software in handling complex hybrid energy variables (Pan et al., 2020). Although Nigeria has a rich solar resource (IEA, 2022), other factors such as the industrial black soot in Port Harcourt are devastating PV efficiency, reducing the daily power production by up to 63.90% (Obuah and Alalibo, 2018). By considering this aggressive derating in the ACO model, the 1.3 MWp array guarantees a 99.9% reliability index. These localized inefficiencies are also opposed by the choice of high-efficiency monocrystalline modules, which corroborates results of Enongene et al. (2019) that the choice of modules determines the viability of PV in humid, cloud-filled southern Nigeria.

The microgrid optimized by the ACO has far-reaching economic implications on the University of Port Harcourt. Comparing the solar-hybrid system with the generation cost of diesel-dependent generation of $0.562/kWh, a 57% decrease in the localized cost of electricity is introduced. This is especially important since the current price of self-generated diesel electricity in Nigeria is more than ₦70/kWh because of the increasing retail diesel prices and the elimination of subsidies (Adesanya and Schelly, 2019). The imported inflation is cushioned by the optimized LCOE of $0.244/kWh. This is consistent with Akinsipe et al. (2020) and Obi et al. (2019) who discovered that the initial high start-up costs of renewable infrastructure are soon recouped through the removal of the ongoing diesel spending. Having a discounted payback period of 9 years exactly and a terminal Net Present Value (NPV) of $1.457 million in a 25-year lifecycle, the Demand-First ACO framework provides a very profitable, scalable model of sustainable institutional electrification.

1.2 CONCLUSION

The erratic power supply and exorbitant cost of diesel generation at the University of Port Harcourt present significant barriers to academic continuity and institutional sustainability. This study successfully demonstrated the application of an Ant Colony Optimization (ACO) algorithm, integrated with a Demand-First framework, to design a technically robust and economically viable megawatt-scale solar-hybrid microgrid. By implementing a 10% Demand-Side Management (DSM) strategy, the daily campus load was optimized to 3,780 kWh. This load reduction allowed the ACO model to avoid costly oversizing, converging at a global minimum cost configuration of a 1.3 MWp monocrystalline photovoltaic array paired with a 1.0 MWh Lithium Iron Phosphate Battery Energy Storage System (BESS).

The techno-economic evaluation confirms that transitioning from the diesel-heavy baseline to this optimized architecture reduces annual operational expenditures by 57%, generating approximately $0.44 million in yearly savings. Requiring an initial capital expenditure of $2.525 million, the proposed system achieves a Levelized Cost of Energy (LCOE) of $0.244/kWh and reaches a discounted break-even point in exactly 9 years. Furthermore, generating a terminal Net Present Value (NPV) of $1.457 million over a 25-year operational lifecycle conclusively proves that metaheuristic optimization is a critical, highly profitable tool for addressing sustainable institutional electrification in Nigeria.

6. Recommendations

The following actionable recommendations are proposed for the University of Port Harcourt and future energy stakeholders:

1. The University administration should leverage the positive Net Present Value (NPV) and 9-year payback metrics established in this study to actively pursue green energy financing, international educational grants, or Public-Private Partnerships (PPPs) to secure the $2.525 million CAPEX required for deployment.
2. To guarantee the system operates within the optimized 3,780 kWh/day threshold, the university must enact a strict, campus-wide energy policy. This includes retrofitting buildings with energy-efficient appliances, scheduling heavy laboratory equipment usage

to align with peak solar hours, and eliminating phantom loads in administrative blocks after hours.

3. Given the region's prevalent black soot pollution, which severely degrades panel efficiency, the university must establish a dedicated technical team for high-frequency maintenance. A strict cleaning schedule must be adhered to during the dry season to prevent the 32% to 63% efficiency drops noted in regional literature.
4. Future academic research should explore the integration of Internet of Things (IoT) sensors for dynamic, real-time load shedding. Additionally, as the Nigerian Electricity Regulatory Commission (NERC) continues to update grid policies, subsequent studies should evaluate the economic potential of a grid-tied configuration, exploring whether the university could generate secondary revenue by exporting excess weekend solar generation back to the national grid.

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