

Integrated Supply and Demand Side Management of Grid-Connected Hybrid Renewable Energy Systems for Sustainable Power Supply

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Abstract— Unreliable and poor cost of electricity supply is a major problem facing healthcare institutions in Nigeria, especially those within the Band A category. Health care centres that offer primary health care are particularly susceptible to outage, high energy rates, and poor reliability. These issues are not only making operations expensive but are also undermining service delivery, necessitating the need to have sustainable solutions to energy management. The research paper set out to design and test energy management measures that will increase cost-effectiveness, reliability, and sustainability of electricity supply in the Rumuigbo Primary Health Centre. A hybrid renewable energy system, which includes solar PV generation, battery storage, and grid support, was modeled, and an integrated supply- and demand-side management was modeled in MATLAB/Simulink. The daily load data were involved to profile the facility demand which was 92.08 kWh/day with an average power demand of 3.836 kW. Three grid-only, SSM (PV-BESS), and SSM-DSM operational scenarios were simulated and evaluated using load performance, energy expenditures, peak demand fee and total bills under the current Band A tariff. The analysis showed that the daily load met by the facility is 92.08 kWh/day, whereby the maximum power demand was 3.836 kW with the highest demand being in the Resident Doctors Quarters (15.47%), Nurses Station (13.90%), and the Doctor/Matrons offices (11.64% each), which made up more than half the total energy consumption. The grid-only scenario was the most unattractive one, whereby consumption of 1.5-5 kWh, energy charges of ₦314-₦1,048, demand charges of ₦2,000/kW, and the overall bills of ₦3,000 were the order of the day. The SSM plan decreased grid reliance to 1-3 kWh, minimized energy expenses to ₦200-₦600, limited demand charges to ₦1,200/kW, and limited the bill to ₦800-₦200, saving 41 percent of energy costs, 30 percent overall bill. This integrated SSM-DSM approach brought the most favorable result and kept the consumption of 0.35-0.6 kWh, minimizing the energy bill to ₦60-₦110, the demand charge to ₦150-₦220/kW, and decreased the total bill to ₦200-₦300, achieving the overall cost reduction of 88% and being fully independent of the grid. The paper has made an analysis that, despite the significant economic and operational advantages of supply-side management (SSM), the most effective way to attain long-term sustainability is the combination of demand-side management (DSM) and PV-BESS systems.

Keywords— Hybrid Renewable Energy System, Solar PV-Battery Energy Storage System (PV-BESS), Supply-Side and Demand-Side Management (SSM-DSM), Electricity Cost Optimization, Primary Healthcare Energy Sustainability.

I. INTRODUCTION

The global energy landscape is undergoing a significant transformation driven by the urgent need to reduce greenhouse gas emissions, expand access to reliable electricity, and ensure long-term environmental sustainability (WRI, 2025). Conventional power generation systems, largely dependent on fossil fuels such as coal, oil, and natural gas, have historically dominated electricity production. However, their environmental consequences—including increased carbon emissions and climate change—combined with concerns over resource depletion, have rendered them increasingly unsustainable (IEA, 2025). In response, renewable energy sources (RES) such as solar, wind, and biomass have emerged as cleaner and inexhaustible alternatives capable of supporting sustainable development goals (Olatomiwa et al., 2025). Despite their environmental and economic advantages, renewable energy systems present notable technical challenges. Solar photovoltaic (PV) generation, for instance, is inherently intermittent due to its dependence on weather conditions and daylight availability (Akinbami et al., 2022). Variations in generation, when combined with fluctuating load demand, can create power imbalances that compromise system stability, reliability, and efficiency (Olatomiwa et al., 2016). These challenges are particularly pronounced in developing countries

like Nigeria, where the existing grid infrastructure is often outdated and lacks the flexibility required to accommodate the variable nature of solar energy (AUN, 2025). Grid-connected Hybrid Renewable Energy Systems (HRES) have been proposed as a viable solution to address these concerns. By integrating solar PV generation, battery energy storage systems, and grid interconnection, HRES enhance energy security, improve operational flexibility, and reduce reliance on fossil fuels (Olatomiwa et al., 2022). However, the effectiveness of such systems depends heavily on advanced energy management strategies capable of coordinating variable generation with real-time consumer demand. Existing energy management approaches have predominantly focused on supply-side strategies, including generation control, battery dispatch, and grid support mechanisms (MDPI, 2025). While these methods contribute to system stability, they often overlook the substantial potential of demand-side management (DSM). With the increasing adoption of smart appliances and medical equipment in healthcare facilities, electricity demand has become more dynamic (Silva et al., 2020). Without structured DSM strategies, such as load shifting and peak shaving, opportunities to enhance system optimization remain underutilized (SCIRP, 2024). The limited integration of supply-side management (SSM) and DSM in grid-connected systems has resulted in operational inefficiencies, higher costs, and

occasional load shedding (Olatomiwa et al., 2022). To address these gaps, this study develops an integrated SSM and DSM framework. Using the Rumuigbo Primary Health Care Centre in Port Harcourt, Rivers State, Nigeria, as a representative case study, the research aims to enhance operational efficiency, improve reliability, and ensure a continuous, sustainable power supply for essential healthcare infrastructure (SEAHI, 2025).

II. METHODOLOGY

A hybrid renewable energy system (HRES) that is connected to the grid is simulated and its components are utilised in this research. For creating, integrating, and testing the supply-side and demand-side management (SSM-DSM) framework, the system was planned and executed in MATLAB/Simulink, a simulation environment. The integrated framework incorporates a categorized load profile from the Rumuigbo Primary Health Care Centre, Port Harcourt for demand-side management, an MPPT-equipped solar PV array for optimized generation, and a dynamic Battery Energy Storage System (BESS) for backup, all interfaced through a controlled DC-AC inverter system to a three-phase utility grid capable of both grid-connected and islanded operations.

2.1 Load Profile Estimation of Rumuigbo Primary Health Care Centre

Proper load profiling is a very important process in designing and operation of hybrid renewable energy. It entails the examination of the electricity use pattern of the facility to comprehend the when, the magnitude and the category of loads. The load profile of the case study is presented in the appendices. *Daily Energy Consumption (Wh/day)*

The daily energy requirement of each load was first determined by multiplying its rated power by the number of operational hours, expressed as:

$$E_{day,Wh} = P_{load} * t \quad (1)$$

Where
 $E_{day,Wh}$: daily energy consumed by the load in watt-hours
 P_{load} rated power of the load(W)
 t : total operating hours per day (h)
Daily Energy Consumption (kWh/day)

The daily consumption was converted from watt-hours to kilowatt-hours using

$$E_{day,kWh} = \frac{E_{day,Wh}}{1000} \quad (2)$$

Where
 $E_{day,Wh}$: daily energy consumed by the load in watt-hours
Percentage Contribution of Each Load

To establish the relative share of each unit in the total facility demand, the percentage contribution was computed as

$$\% load = \frac{E_{day,kWh}}{E_{total,kWh}} * 100 \quad (3)$$

Where
 $E_{day,kWh}$: daily energy consumed by the load in kilo watt-hours
 $E_{total,kWh}$: Total energy consumed by the load in kilo watt-hours

Average Power Demand (kW)

The average continuous power demand of each unit was obtained by normalizing the daily energy consumption over 24 hours

$$P_{avg} = \frac{E_{day,kWh}}{24} \quad (4)$$

Where

$E_{day,kWh}$: daily energy consumed by the load in kilo watt-hours

2.2 Modeling of Grid connected Hybrid Renewable Energy System Incorporating Solar, and Energy Storage System.

Solar Power Generation

The instantaneous power output from the solar panels depends on solar irradiance, panel area, and efficiency and is given by

$$P_{PV}(t) = A * G(t) * \eta_{PV} \quad (5)$$

Where;

$P_{PV}(t)$: power generated by the photovoltaic system at time, t

A : area of the solar panels (m²)

$G(t)$: solar irradiance at time t (W/m²)

η_{PV} : efficiency of the photovoltaic system

Integrating (3.5) gives Energy per day

$$E_{daily} = \int_0^{24h} P_{PV}(t) dt \quad (6)$$

$$E_{daily} = A\eta_{PV} \int_0^{24h} G(t) dt \quad (7)$$

$$peak \text{ sun hour (PSH)} * 1000 = H \quad (8)$$

$$E_{daily} = A\eta_{PV} * H \quad (9)$$

$$PV_{(kWp)} = A\eta_{PV} \quad (10)$$

$$PV_{(kWp)} = \frac{E_{daily}}{PSH * Derating \text{ Factor}} \quad (11)$$

Where

A: area of panel

E_{daily} : daily energy consumed by the load in kilo watt-hours

PSH: peak sun hour:5hr

Derating factor: 0.8

Battery Storage

Battery energy storage is essential for stabilizing intermittent renewable generation from solar and wind. The battery's state of charge (SoC) changes based on the charging and discharging processes. The change in battery energy.

$$SoC(t) = SoC(t - 1) + \frac{\eta_{charge} * P_{charge}(t) - \frac{P_{discharge}(t)}{\eta_{discharge}}}{E_{bat}} \quad (12)$$

Where;

$SoC(t)$: state of charge at time (t)

$P_{charge}(t)$: power used to charge the battery (W)

$P_{discharge}(t)$: power discharged from the battery (W)

η_{charge} and $\eta_{discharge}$: efficiencies for charging and discharging the battery

E_{bat} : battery capacity

$$Battery \text{ kWh} = \frac{E_{daily} * \text{Autonomy days}}{DoD * \eta} \quad (13)$$

Where

E_{daily} : daily energy consumed by the load in kilo watt-hours

Autonomy Days: 1

DoD: Depth of discharge 80%

η : Battery efficiency 90%

2.3 Utility Grid

Grid interaction for a distributed generation (DG) system can be modeled by considering both the power exported to the

grid and the power imported from the grid. If renewable generation is low and battery could not meet the load demand, then the power deficiency is purchased. The imported power from the grid is given by

$$P_{grid}^{imp} = \min(P_d(t) - P_{pv}(t) - P_b^{out}(t)) \quad (14)$$

Similarly, if the total generation from renewable sources and batteries exceeds the load demand, the surplus power is exported. The exported power to the grid is given by

$$P_{grid}^{exp} = \max(P_{pv}(t) + P_b^{out}(t) - P_d(t)) \quad (15)$$

Where

$P_d(t)$: total power demand at time

$P_{pv}(t)$: power from Solar PV Generation

$P_b^{out}(t)$: power supplied by the Battery

2.4 Design a Supply-Side Management Algorithm for Optimal Dispatch of Available Energy Resources.

To ensure reliable and cost-effective operation of the hybrid renewable energy system, an optimized supply-side management algorithm is required. This involves the

coordinated dispatch of solar PV, and energy storage systems to balance supply with demand while minimizing grid import cost and maximizing renewable energy utilization. The objective function is to minimize the total operating cost over the scheduling horizon given by;

$$\min C_{op} = \sum (C_{grid}(t) + C_{pv}(t) + C_{bat}(t)) \quad (16)$$

Subject to

$$\text{Battery SOC limits: } SoC_{min} \leq SoC(t) \leq SoC_{max} \quad (17)$$

$$\text{Power Limit: } 0 \leq P_{bat}(t) \leq P_{bat}^{max}$$

$$\text{Grid import Limit: } 0 \leq P_{grid}^{import}(t) \leq P_{grid}^{max,import} \quad (18)$$

2.5 Simulation

The design and analysis in this paper applied simulation-based design and analysis using MATLAB/Simulink to design and analyze an integrated Supply and Demand Side Management (SSM-dsma) of a Hybrid Renewable Energy System (HRES). This proposed solution ensured that active synchronization was done between the energy and the demand side load arrangements, which improved the effectiveness of the systems, reliability and cost-effectiveness.

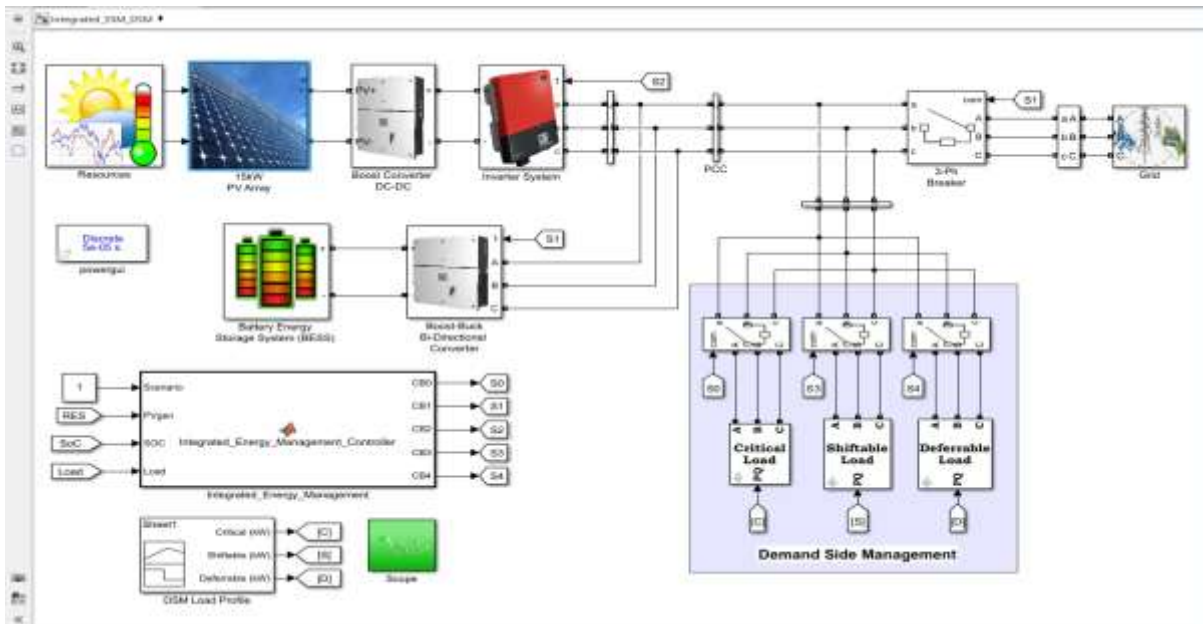


Figure 1: MATLAB/Simulink Model of a Grid-Connected Hybrid Renewable Energy System with both Supply and demand-side Management Strategy

Figure 1 is a MATLAB/Simulink model of a Grid-Connected Solar PV-Battery Hybrid Renewable Energy System which combines both supply-side and demand-side management (SSM-DSM). The framework works in a coordinated system whereby the supply dispatch module identifies the available energy sources depending on load levels and source availability and the DSM module adjusts or restrains loads to match current supply conditions.

A threshold-based dispatch strategy was embraced on the supply side. The grid was used as the main source of loads within a specified threshold with the additional demand being handled by the renewable and storage sources. Photovoltaic

(PV) generation was given a priority to provide supplemental demand during generation and the Battery Energy Storage System (BESS) would discharge within the state-of-charge (SOC) limits when the PV power was not available. In case the joint capacity of the PV and BESS was not sufficient to cater to the demand, the grid provided the deficit. The demand side is classified and grouped into critical, shiftable, and deferrable loads with scheduling or curtailment implemented depending on the availability of energy. The general control logic which is applied in MATLAB/Simulink with logical decision blocks to simulate various operating scenarios.

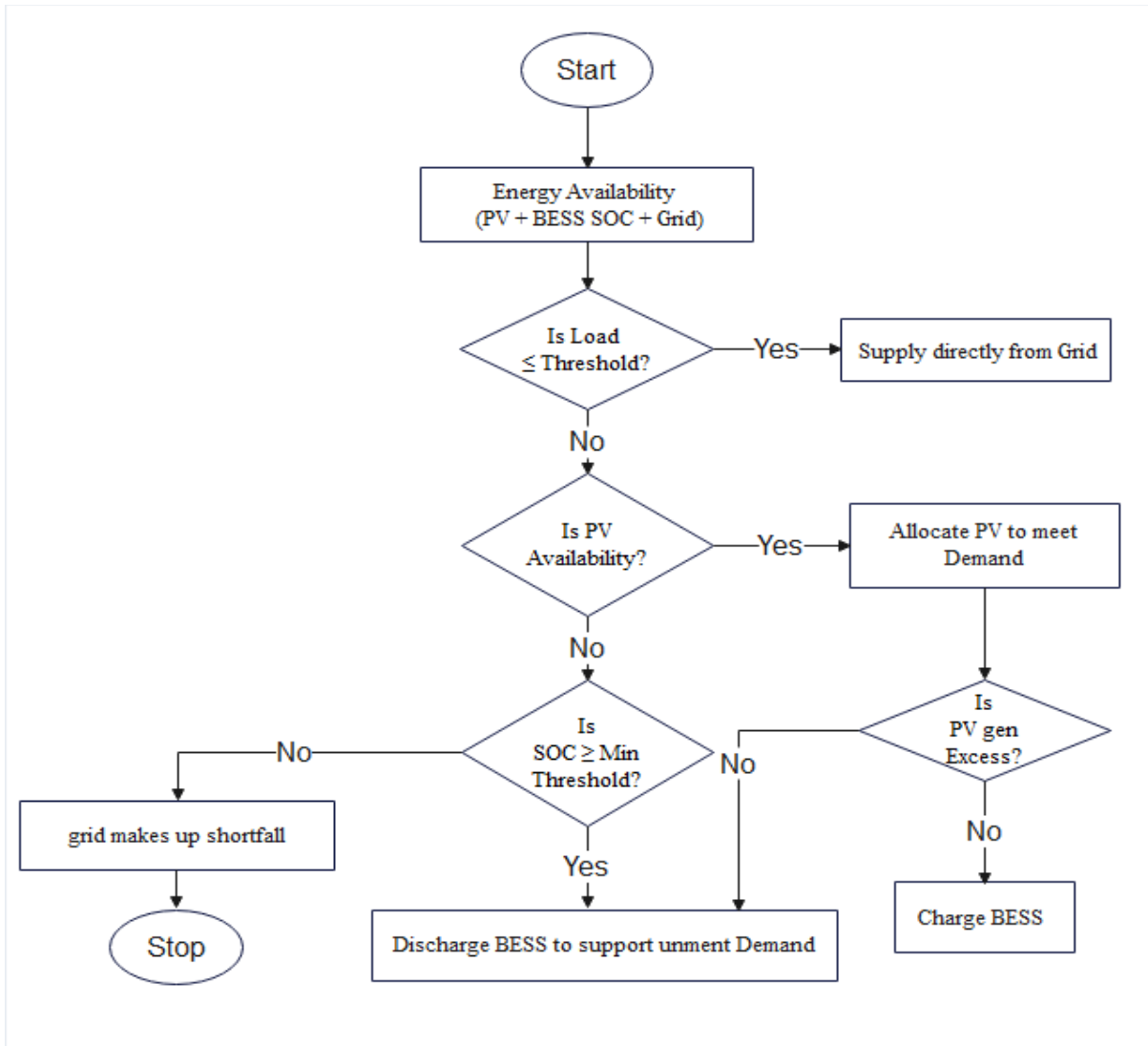


Figure 2: Flowchart of the Supply-Side Management

A MATLAB/Simulink model of a Grid-Connected Solar PV-Battery Hybrid Renewable Energy System is achieved in Figure 1 and integrates a supply-side management (SSM) and a demand-side management (DSM). The framework operates in a coherent system according to which the supply dispatch module defines the available sources of energy by the level of load and availability of the sources and the DSM module regulates or limits loads to the current supply conditions. The supply side adopted a threshold-based dispatch strategy. The grid served as the primary source of loads in a set limit with the supplementary demand being met by the renewable and storage sources. A priority was assigned to photovoltaic (PV) generation to make up some additional demand during generation, and the Battery Energy Storage System (BESS) would discharge within the state-of-charge (SOC) limits when PV power was unavailable. The deficit was supplied by the grid in case the joint capacity of the PV and BESS was inadequate to meet the demand. The demand is divided and categorized into critical loads, shiftable loads and deferrable loads; schedules or curtailment is applied based on energy availability.

The general control logic that is being utilized in MATLAB/Simulink with logical decision blocks to model different operating situations.

Develop a Demand-Side Management Strategy to Regulate and Optimize Consumer Load Profiles

As a supplement to the supply side optimization, a demand side management (DSM) approach is formulated to control and optimize consumer load profiles. Its aim is to reduce the overall electricity bill by scheduling the flexible loads optimally to those times of the day when the grid prices are lower or renewable energy is more. This will minimize dependence on expensive grid imports, decrease pressure on the power grid, and increase the use of renewable energy. The objective function is formulated:

$$\min C_{DSM} = \sum_t P_{load}^{DSM}(t) \cdot \lambda(t) \tag{19}$$

Where

$\lambda(t)$: is the cost of consuming electricity at that hour.

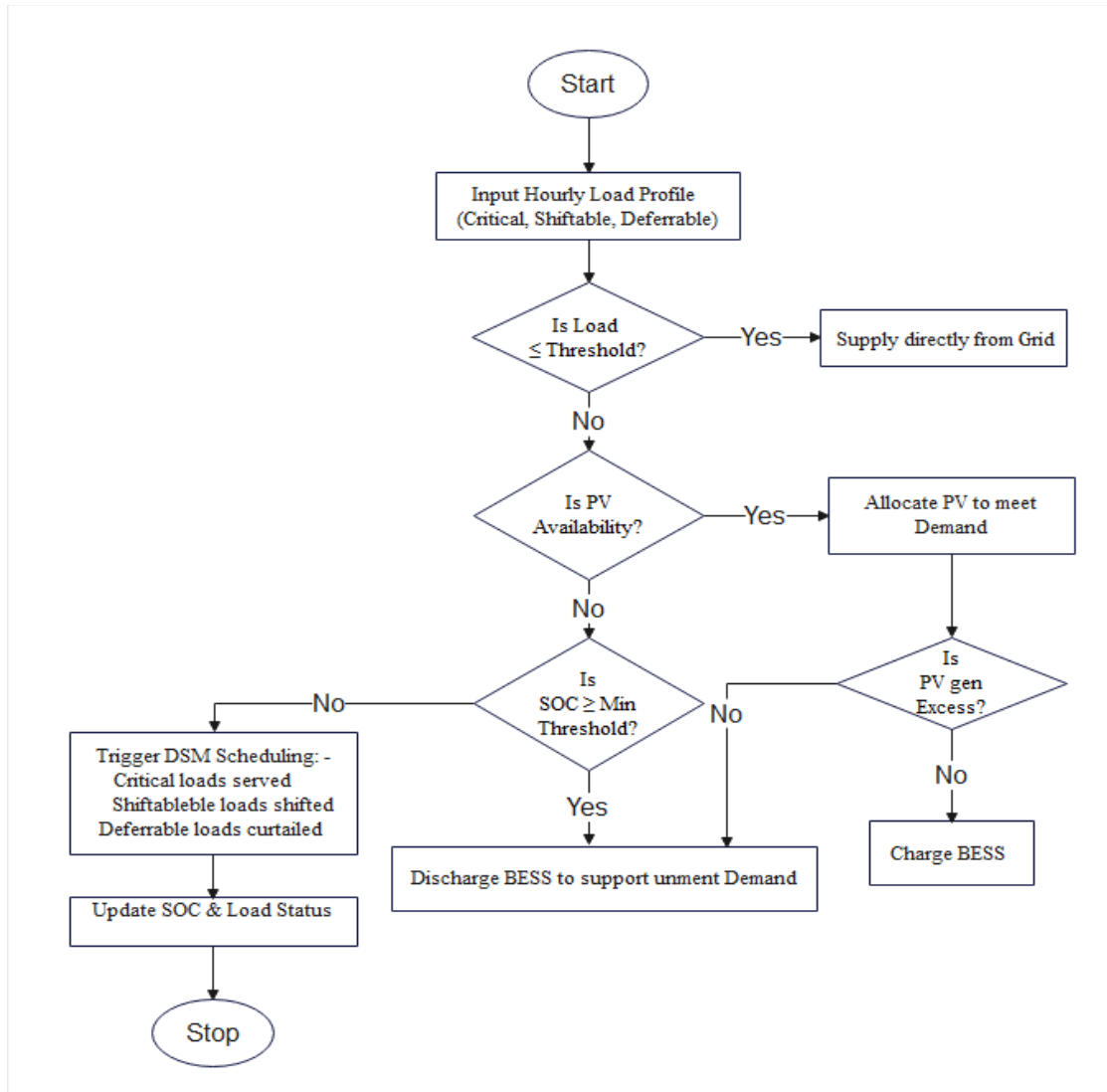


Figure 3 Flowchart of the Demand-Side Management

The operational flowchart of photovoltaic (PV) generation, battery energy storage systems (BESS) and grid supply of the study facility is presented in the Demand Side Management (DSM) flowchart (Figure 3). This is initiated by the input of the hourly load profile that is divided into critical, shiftable and deferrable loads that form the basis of the hierarchical decision-making in the allocation of supply. In every stage, the algorithm was first determine whether the load has reached a threshold limit. In case of satisfaction the demand is provided at the grid level without intervention of DSM. But when the load is above this threshold, the availability of resources is determined in a sequence whereby PV is the first to be determined: in the case of PV availability, it is used to satisfy the load demand and the remaining is channeled to charge the BESS. In the case of PV being unsatisfactory, the controller examines the BESS state of charge (SOC) and when SOC is satisfactory, the battery is discharged to power additional demand. Finally, when PV and BESS are insufficient, then DSM scheduling occurs where shiftable loads are become rescheduled, whereas deferrable loads are curtailed, and critical loads are always served. Lastly,

the system updates SOC and load status, which makes the system operate adaptively throughout the day. This model enhances power security, maximizes the use of renewable energy sources, and lessens reliance on the grid.

Integrate Both Strategies into a Unified Control System for Coordinated Operation

To achieve sustainable and efficient operation of the hybrid renewable energy system, supply-side management and demand-side management strategies must be integrated within a unified control framework. This coordinated approach enables optimal dispatch of generation resources alongside adaptive load regulation, ensuring balanced power flow, reduced operating costs, and enhanced renewable energy utilization. The combined objective function is given by

$$\text{min} J = w_1 C_{op} + w_2 C_{DSM} \quad (20)$$

Where

C_{op} : supply-side operational cost

C_{DSM} : demand-side cost

w_1, w_2 : weighting factors for cost-reliability trade-off

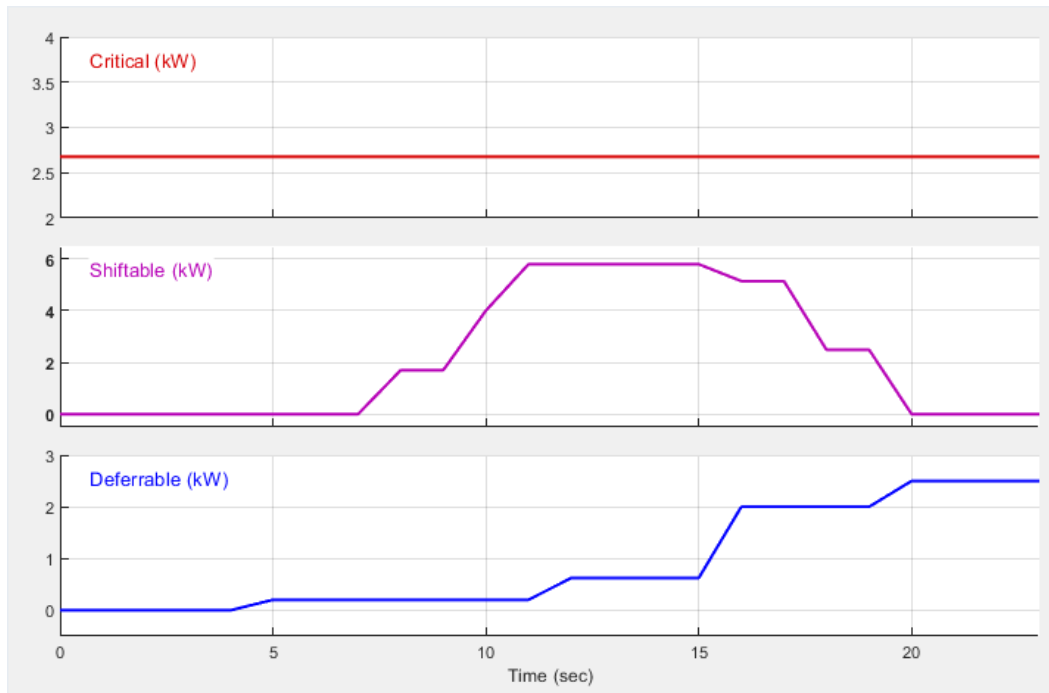


Figure 4 Demand Side Management Load Profile Categorization

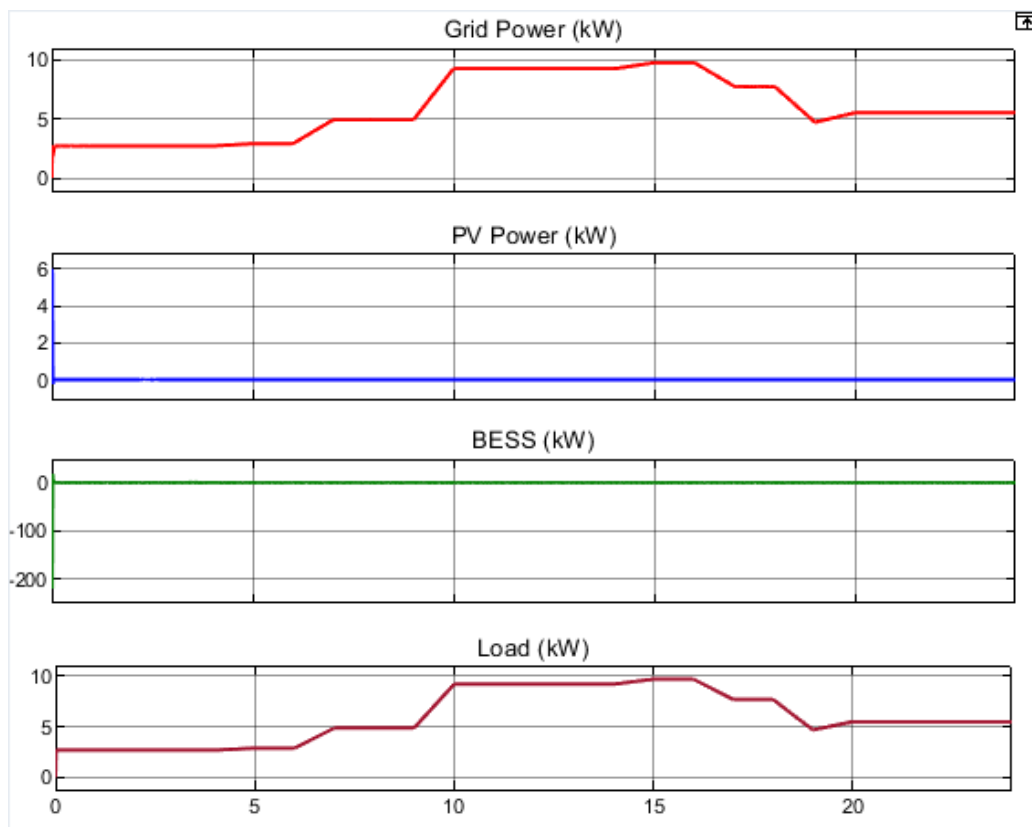


Figure 5: Base-Case Simulation Results with Grid-Only Power Supply Scenario

III. RESULT

3.1 Base-Case Simulation with Grid-Only Scenario

The base-case simulation in Figure 5 presents the values of the electricity demand provided by the grid as the entire supplier. In this case, load demand is approximately 3 kW to 10 kW throughout the day with the same pattern being followed by

grid power profile nearly in the same manner, as there is no contribution by the other sources to supply. The photovoltaic (PV) system and the battery energy storage system (BESS) are both inactive and so give zero output during the simulation. This implies that the grid takes all the burden of demand satisfaction which guarantees supply with significant disadvantages. Using the grid alone is more expensive and the system is prone to failure as well as ignoring the possible advantages of renewable energy. There is no contribution of clean sources in the absence of PV power, and the unused BESS

eliminates the chance of storing the surplus energy or covering the grid during peak hours. Consequently, the grid is under great stress when there is a peak of demand, which in practice may result in inefficiencies and an increase in transmission losses. This base case is significant in that it gives a clear point of reference: it demonstrates what will be the result in case nothing is done in terms of renewable or storage systems, and it was used to compare the extent to which the system can be better once PV and BESS are implemented to enhance sustainability, resilience, and efficiency.

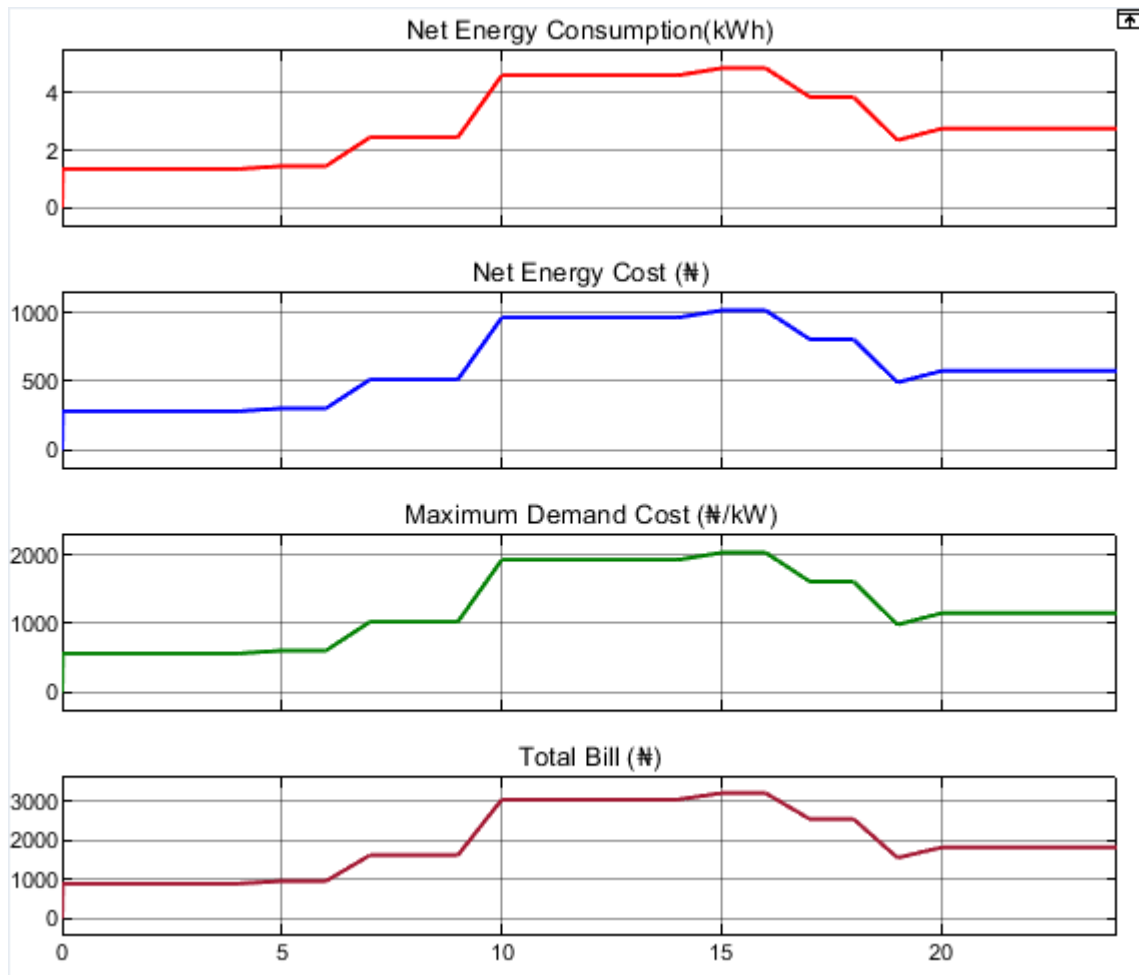


Figure 6: Electricity Cost Performance for Grid-Only Supply at Rumuigbo Health Centre

Figure 6 shows the economic management of a base-case scenario of the grid-only case of the Rumuigbo Health Centre in which the facility falls in the band A with an existing tariff rate of N209.50/kWh. Net energy consumption profile demonstrates the demand varying between 1.5 kWh in the low-load period and 5 kWh in the peak hours, which are directly proportional to the energy costs. With such a tariff rate the off-peak cost of energy is approximately N314 whilst peak demand is raising the cost to nearly N1,048, illustrating how sensitive the outlay spent on energy is towards changes in load. The maximum demand cost, which represents the price that accompanies the highest momentary load, is between approximately N600/kW at the lower end to almost N2,000/kW at peak demand which means that the cost of running at higher

levels of power is quite expensive. Therefore, the overall cost of the health center varies with N1,000 when the load is low and more than N3,000 when fully loaded, due to energy consumption fees, and costs depending on demand respectively. The findings indicate that the sole dependence on the grid creates significant financial strain on healthcare facilities, and especially in Band A in which tariff rates are the highest. The cost curve reveals that there are no mitigating measures being implemented like PV generation or BESS, which can otherwise balance the consumption and balance peak demand. This initial analysis sets a critical standard against which the possibilities of saving costs in future situations when the renewable insertion and the demand-side control plans are implemented to improve economic and functional effectiveness are assessed.

3.2 Supply-Side Management Strategy Implementation

Figure 7 shows how a supply-side management (SSM) strategy can be implemented by making photovoltaic (PV) generation the core of the supply and grid the backup supply, and battery energy storage system (BESS) controlled by an adaptive control algorithm. The load will vary with off-peak hours of 3 kW and peak demand of about 10 kW, PV-generated power will be constant at 13-14 kW steadily higher than that of the load. The control strategy determines how the system will operate in that, when PV generation is more than 12 kW and battery SOC is less than 80 percent, the BESS will be charged so that the excess solar energy is stored instead of being wasted. On the other hand, the BESS should discharge to become less dependent on the grid in case SOC is larger than 30% and both the PV and the stored energy can supply a portion of 60 or more of the loads. The charging is once more given priority in the cases that the PV output is greater than the load and yet the SOC, still below 80 percent, thus maximizing solar utilization. In case all the above-mentioned conditions are not satisfied, the grid offers supply support, and PV keeps on contributing when it is available. In this logic of control, the role of the grid becomes minimal, with the case of the near-zero grid power profile, which indicates some instances of upward shifts when there is a demand spike and downward shifts indicating possible cases of export. This integrated approach will make sure that there is a maximum use of renewable generation, a reduction in

grid dependency, and that when possible, BESS charging opportunities should be utilized

Figure 8 demonstrates the economic performance of the supply-side management (SSM) strategy adopted in the Rumuigbo Health Centre where the photovoltaic (PV) generation is a major energy source, the grid is used as a backup source, and the battery energy storage system (BESS) is managed adaptively. The net energy consumption profile indicates that grid reliance has been greatly reduced and at times it goes down to 1 kWh when the demand is low and up to approximately 3 kWh when the load is very high hence reducing the energy bills appropriately. It is relatively cheap on the current tariff of Band A N209.50/kWh: the net energy cost is no more than N200 at off-peak demand and slightly above N600 at times when the grid imports are at the peak of the load process. Maximum demand cost, which indicates utility costs as a result of peak power consumption, is as high as approximately N1,200/kW at the peak but lower than in the grid-only case because of the balancing influence of PV and BESS assistance. As a result, the total bill in light-load conditions is N800, whereas it is around N2,000 when the ride is at peak hours, which proves to be a significant saving relative to the base case. These findings point to the efficiency of PV integration in hedging grid power and the adaptive BESS management to reduce costs associated with demand, and enhancing the overall economic viability of the facility to supply energy.

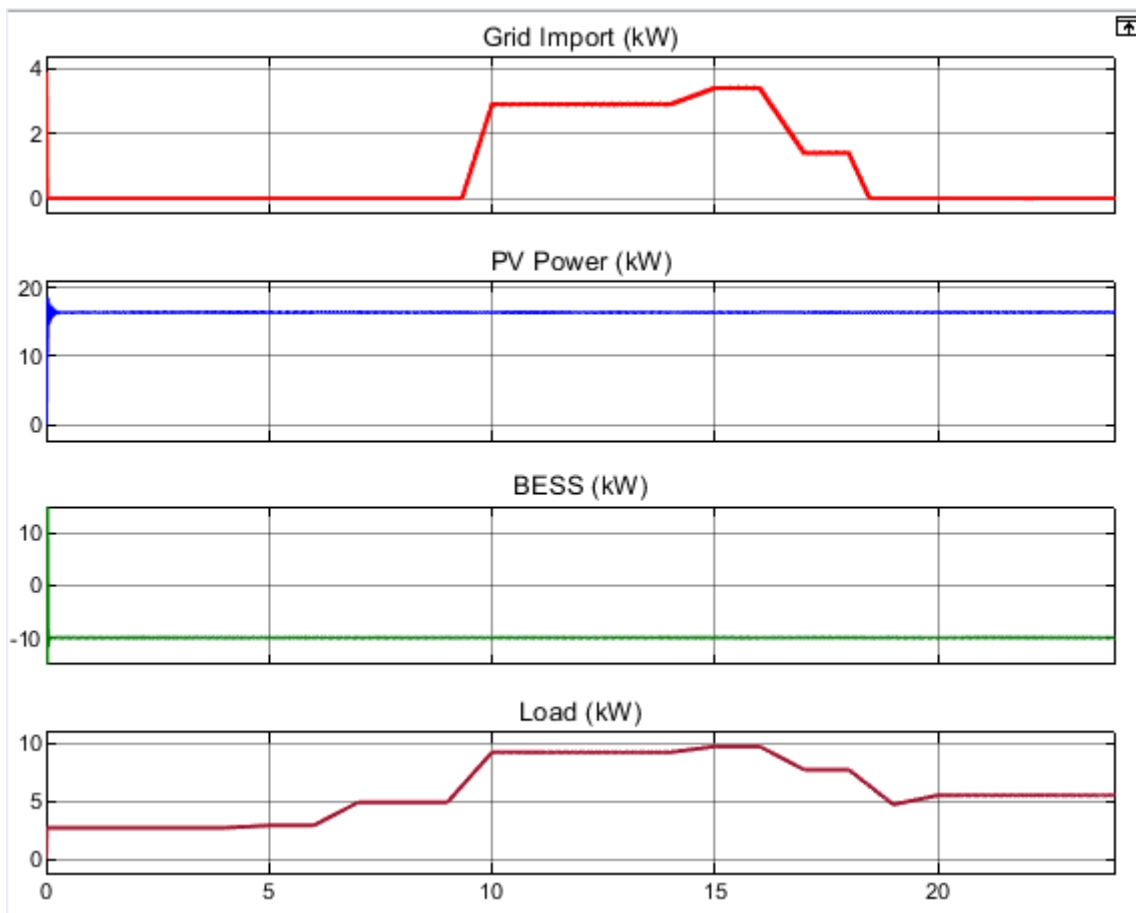


Figure 7: Electricity Supply under Supply-Side Management (SSM) Strategy

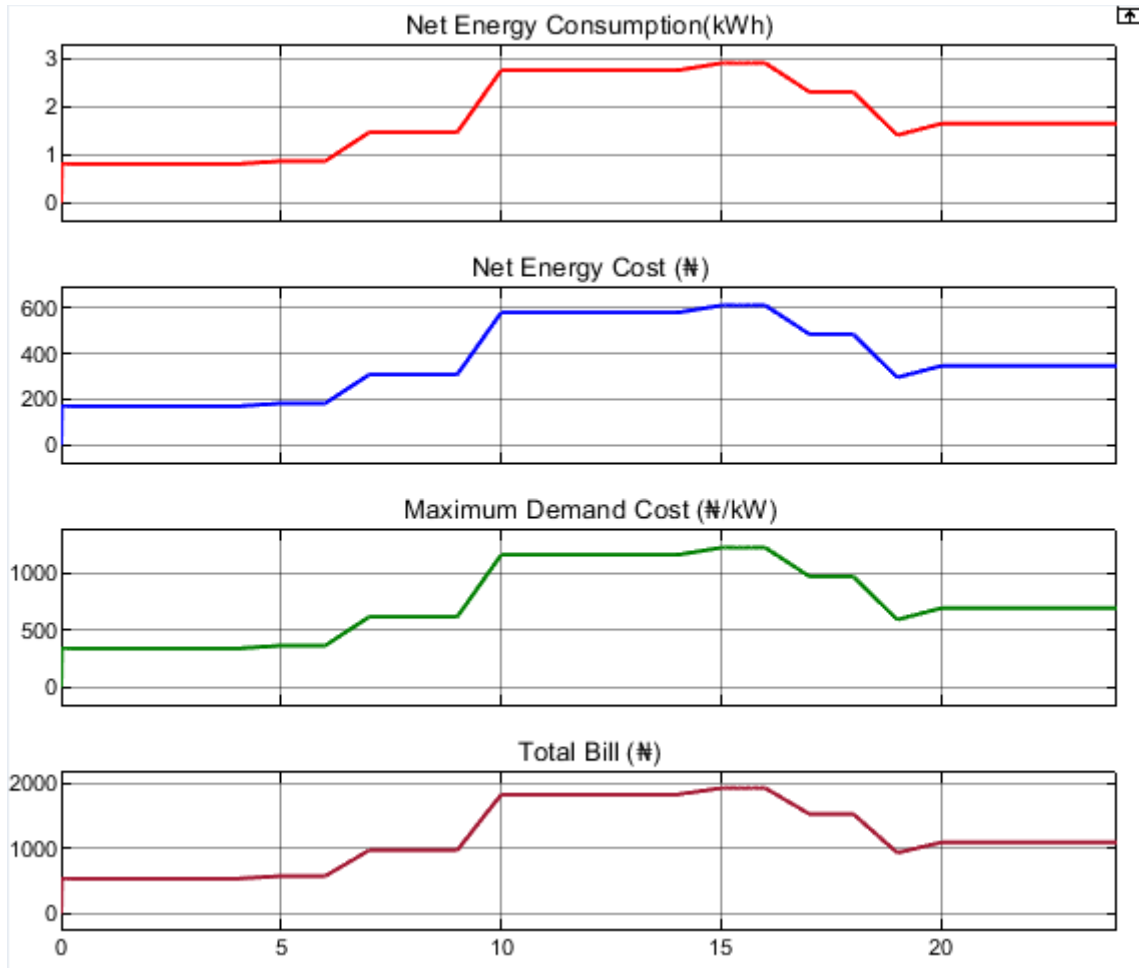


Figure 8: Electricity Cost Performance after Implementing Supply-Side Management (SSM) Strategy at Rumuigbo Health Centre

3.3 Integrated Supply-Side and Demand-Side Management Strategy

The figure 9 shows the performance of an integrated supply-side and demand-side management (SSM-DSM) strategy of the Rumuigbo Health Centre. The generator of photovoltaic (PV) is determined as the most important source of supply in this scheme, providing approximately 18-19 kW all the time, which is quite significant compared to the small demand of 2.5-4 kW of the facility. The control system also ensures that excess PV power is also sent to battery energy storage system (BESS) when its state of charge (SOC) falls below 80, which leads to a constant charging rate of about -10 kW over the course of operating period. When the SOC is high enough to get above 30, the controller lets the BESS fill the load when it is needed but gives higher priority to the use of PV. Notably, the grid is not used at all during the simulation, which indicates the strength of the SSM logic in terms of obtaining the dominance of renewable sources and gaining the independence of the grids. DSM mechanisms are used on the demand side to actively control the load consumption and eliminate over-peaking. The adopted control measure is that when the demand is higher than 3.5 kW, a shiftable load (DSM4) is shed and when larger than 4.5 kW, another load (DSM3) is curtailed. This hierarchical shedding method is necessary to provide a full progression of removing non-critical loads with the aim of stabilizing the load

profile. The demand curve that is obtained indicates a smoother consumption with little fluctuations, which proves the effectiveness of DSM to block load surges that would otherwise initiate increased operational and economic penalties. The combination of the integrated SSM-DSM strategy has a balanced coordination of supply and demand. The maximum PV generation is ensured, the BESS is smartly controlled to accept surplus energy and to supply on demand, and peaks in demand are reduced by selective shedding. Operationally and economically, the strategy will help to remove grid reliance, avoid the exposure to demand-related fees, and improve the resilience of the system. The integrated scenario is a more sustainable and cost-effective way of powering the important health facilities when the tariff is Band A compared to grid-only and SSM-only scenarios.

Figure 10 shows the electricity cost performance of the integrated supply-side management (SSM) and the demand-side management (DSM) strategy that is employed at the Rumuigbo Health Centre in which grid consumption is supplemented by co-ordinated load management with the aim of reducing demand-related charges. The profile of net energy consumption is constant at about 0.35-0.4 kWh and does peak at times to about 0.6 kWh due to short-term load spikes, which is indicative of the controlled demand behaviour by the centre in the integrated strategy.

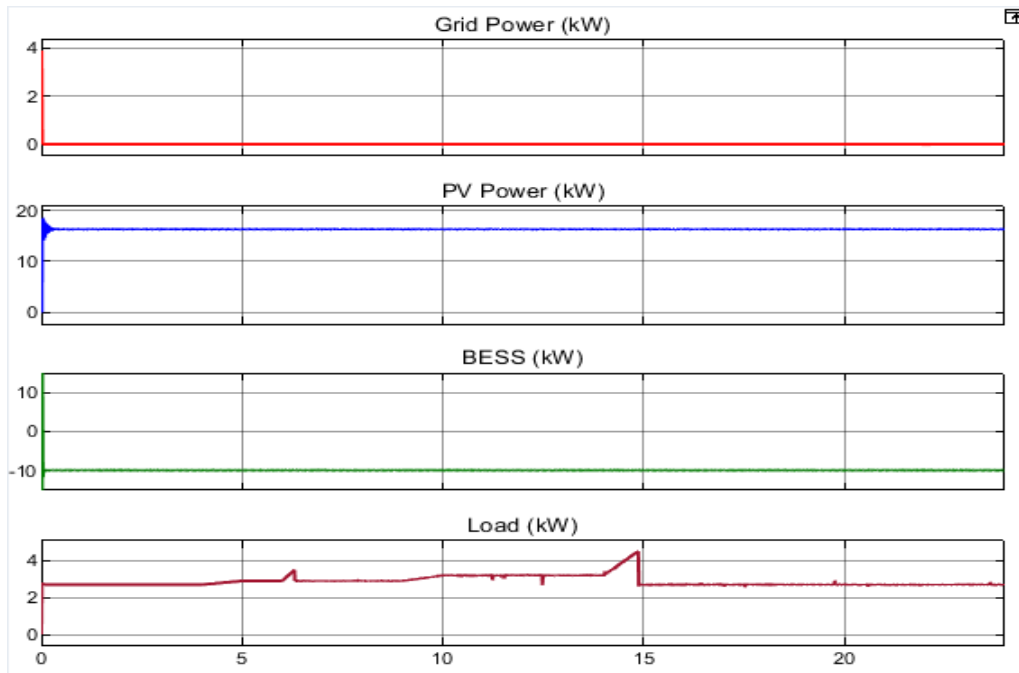


Figure 9: Electricity Supply under Integrated Supply-Side (SSM) and Demand Side Management Strategy

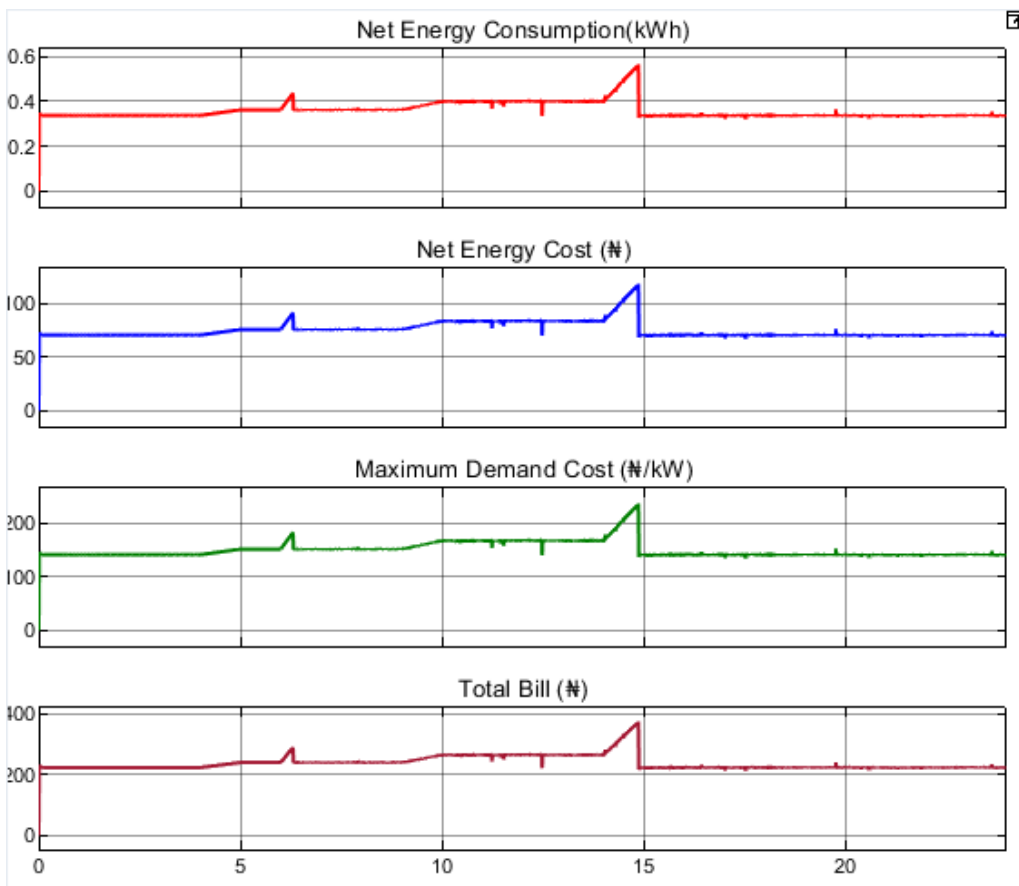


Figure 10: Electricity Cost Performance after Implementing Integrated Supply-Side (SSM) Demand Side Management (DSM) Strategy at Rumuigbo Health Centre

The net energy cost at the current tariff of Band A is kept within a very close band of N60-70, and this can only go up to

approximately N110 at peak hours. Likewise, the maximum demand cost can stabilize around N150-160/kW but goes up to

N220/kW when acute load surges take place, which highlights the enduring role of peak power charges even with the overall demand being dampened. As a result, the overall bill will vary within the range of N200 at normal operating level and a little higher than N300 at transient peak condition which means that cost performance is improved compared to the situation when the consumption is in uncontrolled conditions. These findings demonstrate the usefulness of the combined SSM-DSM approach in decreasing total energy consumption by regulating the energy consumption quantities and the demand rates, which increases the cost-efficiency and financial viability of the healthcare facility in relation to its power supply system.

3.4 Comparative Analysis of Scenarios

TABLE 1: Comparative Key Performance Indicators (KPIs) for Energy Management Scenarios at Rumuigbo Health Centre

Scenario	Net Energy Consumption (kWh)	Net Energy Cost (₦)	Maximum Demand Cost (₦/kW)	Total Bill (₦)
Grid-Only (Base Case)	1.5-5.0	314-1,048	600-2,000	1,000-3,000
SSM (PV + Grid + BESS)	1.0-3.0	200-600	Up to 1,200	800-2,000
Integrated SSM-DSM	0.35-0.6	60-110	150-220	200-300

Table 1 contrasted the key performance indicators (KPIs) of three possible operational scenarios grid-only baseline, supply-side management (SSM) with photovoltaic (PV) and battery energy storage system (BESS) support, and integrated supply-side and demand-side management (SSM-DSM) strategy at the Rumuigbo Health Centre. The grid-only case was the most reliant on utility supply with net energy consumption that varied between 1.5 to 5.0 kWh or a wide range of N314-1,048 of energy cost. This over dependence on grid power was also enhanced by maximum demand charges that went to N2,000/kW which made it hit a total bill of N3,000 at times of peak condition. With the SSM approach, the dependence on the grid was greatly minimized, as the focus of the strategy is on PV production and the dynamic regulation of the BESS, where the energy use was minimized to 1.0-3.0 kWh and the energy price was also decreased to N200-600. The peak demand charges were also reduced and stayed below N1,200/kW and the final bill was in a more reasonable range of N800-2,000, which depicts the stabilizing influence of combining energy sources. The combined SSM-DSM option produced the most desirable result of near flat consumption profile of 0.35-0.6 kWh, with cost of energy being limited to N60-110 and maximum demand charges being limited to N150-220/kW. Thus, the overall bill was kept at a steady level of N200-300, which is a considerable drop in comparison with the grid-only scenario. The findings highlighted the importance of combining DSM and supply side actions because it does not only counterbalance grid imports with renewable contributions but also prevented load peaks that spurred demand charges proactively, resulting in the most economically viable solution to the health facility.

TABLE 2: Percentage Cost Savings of SSM and SSM-DSM Strategies Compared to Grid-Only Baseline

Scenario	Energy Cost Saving (%)	Demand Cost Saving (%)	Total Bill Saving (%)
Grid-Only (Base Case)	0.0	0.0	0.0
SSM (PV+ Grid +BESS)	41.3	7.7	30.0
Integrated SSM-DSM	87.5	85.8	87.5

Table 2 put into focus the level of savings that was realized when more intelligent energy management measures were used in the Rumuigbo Health Centre. The grid-only was the only scenario on which no savings were to be made but this was anticipated since the entire facility was reliant on utility supply. On the implementation of the supply side management (SSM) strategy, the energy bills became lower by approximately 41 and the overall bill decreased by 30. Cost reductions in demand were less significant at approximately 8% because PV and BESS did not manage peak demand but more so minimized grid imports. The best change was recorded in the case of integrated SSM-DSM strategy where approximately 88 percent of energy costs, demand charges and overall bills were saved. This showed how strongly the load management was ingested with renewable and storage technologies not only was the consumption lower, but the peaks causing the high end of the demand charges were suppressed. Practically, the facility shifted out of the bills that frequently were in the grid-only scenario of N3,000 and more, to a predictable and much cheaper cost of but a few hundred naira. The evidence overall showed that SSM offered a sound basis in cost-cutting, but the introduction of DSM had been the key to making the organization economically sustainable in the long run. Some of the comparative graphs of the cost elements have been plotted in figure 4.8 as the amount of savings realized in shifting to the grid-only baseline to the SSM and finally to the integrated SSM-DSM strategy.

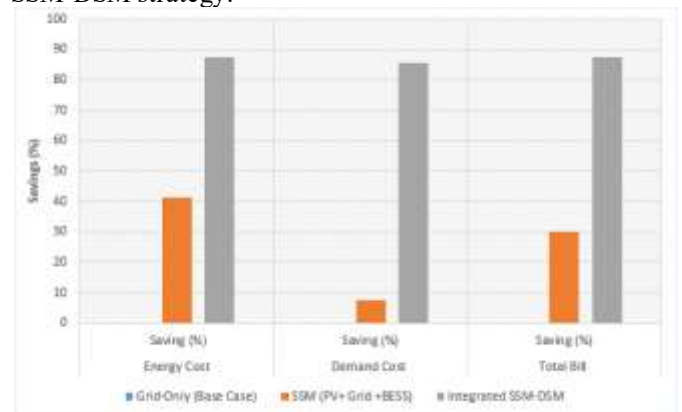


Figure 11: Comparative Plot of Electricity Cost Components under Grid-Only, SSM, and Integrated SSM-DSM Scenarios at Rumuigbo Health Centre

IV. CONCLUSION

The present research showed that the energy demand profile in the Rumuigbo Primary Health Centre can be managed and optimized with the help of strategic supply and demand-side interventions. The initial evaluation proved that the facility has a high dependence on the utility grid, which poses it to the expensive nature, demand fines, and operational risks. The supply-side management (SSM) with the photovoltaic (PV)

generation and battery energy storage (BESS) introduced a great deal of grid reliance and reduced operation expenses, whereas the combination of the supply-and-demand-side management (SSM-DSM) approach turned out to be the most effective in providing close grid independence, cost reduction up to 88%, and system stability. The findings highlight the need to integrate renewable energy with intelligent storage and demand management to provide guaranteed, sustainable, and cost-effective energy to healthcare facilities. In the case of facilities that must work under the conditions of high tariffs, like Band A, these strategies offer a clear way to energy security and economic sustainability in the long term.

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Appendices

Table A1: Matron's Office

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Air condition	1	740	740	8	5,920
Lighting points	4	10	40	8	320
Computer	1	100	100	8	800
Plasma TV	1	100	100	8	800
Refrigerator	1	120	120	24	2,880
Total					10,720 Wh

Table A2: Doctors' Office 1

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Air condition	1	740	740	8	5,920
Computer	1	100	100	8	800
Lighting points	4	10	40	8	320
Plasma TV	1	100	100	8	800
Refrigerator	1	120	120	24	2,880
Total					10,720 Wh

Table A3: Doctors' Office 2

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Air condition	1	740	740	8	5,920
Computer	1	100	100	8	800
Lighting points	4	10	40	8	320
Plasma TV	1	100	100	8	800
Refrigerator	1	120	120	24	2,880
Total					10,720 Wh

Table A4: Maternity/Treatment Ward

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ceiling fans	4	80	320	8	2,560
Lighting points	6	10	60	8	480
Total					3,040 Wh

Table A5: Labour Ward

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ceiling fans	6	80	480	8	3,840
Lighting points	12	10	120	8	960
Plasma TV	1	100	100	8	800
Total					5,600 Wh

Table A6: Nurses Station

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ceiling fans	4	80	320	24	7,680
Refrigerator	1	120	120	24	2,880
Lighting points	6	10	60	24	1,440

Plasma TV	1	100	100	8	800
Total					12800 Wh

Table A7: Pharmacy Unit

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ceiling fans	2	80	160	8	1,280
Refrigerator	1	120	120	24	2,880
Lighting points	4	10	40	8	320
Total					4,480 Wh

Table A8: Record Unit

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Lighting points	4	10	40	8	320
Computer	1	100	100	8	800
Ceiling Fan	1	80	80	8	640
Total					1,760 Wh

Table A9: Immunization Unit

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ceiling fans	4	80	320	8	2,560
Refrigerator	1	120	120	24	2,880
Lighting points	6	10	60	8	480
Total					5,920 Wh

Table A10: Fluid/Sterilization Unit

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Lighting points	4	10	40	8	320
Refrigerator	1	120	120	24	2,880
Total					3,200 Wh

Table A11: Resident Doctors Quarters

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Air condition	1	740	740	8	5,920
Plasma TV	1	100	100	8	800
Ceiling fans	2	80	160	8	1,280
Lighting points	6	10	60	8	480
Refrigerator	1	240	240	24	5,760
Total					14,240 Wh

Table A12: Resident Midwife Quarters

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Plasma TV	1	100	100	8	800
Ceiling fans	1	80	80	8	640
Lighting points	6	10	60	8	480
Refrigerator	1	240	240	24	5,760
Total					7,680 Wh

Table A13: Security Lighting

Appliance	Qty	Unit Power (W)	Total (W)	Hours/day	Energy/day (Wh)
Ext. Lighting points	10	10	100	12	1,200
Total					1,200 Wh

Table A14: Summary of Loads Estimate

Location	Energy/day (Wh/day)
Matron's Office	10,720
Doctors Office 1	10,720
Doctors Office 2	10,720
Maternity/Treatment Ward	3,040
Labour Ward	5,600
Nurses Station	12,800
Pharmacy Unit	4,480
Record Unit	1,760
Immunization Unit	5,920
Fluid/Sterilization Unit	3,200
Resident Doctors Quarters	14,240
Resident Midwife Quarters	7,680
Security Lighting	1,200
Total	92,080