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Integrated Supply-Demand Management for Reliable Power in Grid-Connected Solar PV-Battery Systems in Primary Health Care Facility

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Abstract

Reliable electricity supply is crucial for primary healthcare facilities, especially in rural and semi-urban regions of Nigeria where unstable grid conditions hinder effective medical service delivery. This study develops and evaluates an Integrated Supply and Demand Side Management (ISDSM) framework for a grid-connected solar photovoltaic (PV)-battery hybrid energy system serving the Ahoada Primary Health Care Centre in Rivers State, Nigeria. The ISDSM framework simultaneously coordinates the supply-side (generation, storage, grid import/export) and demand-side (load scheduling, energy efficiency, and demand response) to enhance reliability, reduce cost, and minimize emissions. A simulation-based methodology was implemented using MATLAB/Simulink. Three operational scenarios were analyzed: Grid-only, Supply Side Management (SSM), and Integrated Supply–Demand Side Management (ISDSM). Input data included a 10 kW PV array, 20 kWh lithium-ion battery, average solar irradiance of 5 kWh/m²/day, grid availability of 70%, and a daily facility load of 39.37 kWh. Performance metrics such as energy reliability, cost of electricity, and CO_2 emissions were assessed. Results indicate that the ISDSM configuration achieved the best overall performance, attaining ≈99.8% reliability, ₦41.16 daily energy cost, and 70% emission reduction relative to the grid-only case. Compared to SSM, ISDSM reduced grid imports by 35%, extended battery life through reduced depth-of-discharge, and optimized PV utilization. The study demonstrates that combining DSM strategies with renewable hybrid systems significantly enhances operational resilience and economic sustainability in healthcare facilities. It concludes that ISDSM offers a scalable and cost-effective pathway to achieve uninterrupted, low-carbon power for essential services in Nigeria's healthcare sector.

Keywords: Integrated supply demand side management, solar PV, battery energy storage, primary healthcare, reliability, hybrid power system, Nigeria

INTRODUCTION

The increasing global demand for reliable and sustainable electricity supply has intensified the adoption of renewable energy technologies, particularly solar photovoltaic (PV) systems, as a viable alternative to conventional fossil-fuel-based generation. However, the intermittent and variable nature of solar energy often limits its ability to provide stable power, especially in critical facilities such as primary healthcare centers where uninterrupted electricity is vital for medical operations [1].

The Integration solar PV with battery energy storage systems (BESS) in a grid-connected configuration has emerged as a promising solution, such systems reduce reliance on fossil fuels, thereby, enhancing reliability, energy security, as well as improve flexibility, and operational efficiency [2].

Despite the growing deployment of grid connected hybrid PV-battery systems, many developing regions, including Nigeria, still experience unreliable power supply, resulting in frequent outages and dependence on costly backup generators [3]. However, their successful deployment requires robust management frameworks capable of balancing generation variability with consumer demand in real time. This situation underscores the need for an integrated supply and demand-side management framework that optimizes both energy production and consumption.

Supply-side management focuses mainly on the efficient operation and control of distributed energy resources, while demand-side management (DSM) involves load shifting, demand response, and energy conservation strategies to balance supply and demand in real time [4].

For primary healthcare facilities, reliable power supply is essential for running diagnostic equipment, refrigeration of vaccines, lighting, and other critical services. Hence, integration of demand side management (DSM) strategies with grid-connected PV-battery systems in such facilities, will leads to reduction in operational costs, minimize grid dependency, reduce greenhouse gas emissions, improve energy access and improve resilience [5].

Therefore, developing an integrated supply–demand management framework for grid-connected solar PV-battery hybrid systems presents a sustainable pathway toward achieving reliable, cost-effective, and resilient energy supply for primary healthcare facilities, particularly in developing nations, with a specific focus on the energy demand profile of Ahoada Primary Health Care Centre in Ahoada, Rivers state as a representative study area for decentralized applications.

Statement of the Problem

Access to reliable electricity remains a major challenge for primary healthcare facilities in developing countries, including Nigeria. Frequent power outages, poor grid reliability, and dependence on fossil-fuel generators hinder the effective operation of essential medical equipment and cold-chain systems used for vaccine preservation. Although grid-connected solar photovoltaic (PV) systems with battery storage have shown potential in enhancing power reliability, most existing systems are operated without a coordinated energy management strategy that balances both supply and demand.

The absence of an integrated framework that simultaneously manages the supply side (generation and storage) and the demand side (load prioritization and control) often leads to inefficient energy utilization, frequent battery cycling, and increased operational costs In many hybrid systems, surplus generation from the PV array is underutilized, while peak demand periods still rely on the grid or diesel backup due to poor scheduling and demand response coordination.

Whereas, grid disturbances such as voltage fluctuations or outages disrupt system stability, affecting the continuous power supply needed for healthcare operations.

This study addressed the problem of lack of an integrated supply and demand management framework capable of optimizing the performance of grid-connected solar PV-battery hybrid energy systems for critical facilities, by proposing the development of a unified energy management model that ensures optimal energy dispatch, reduces dependence on fossil backup systems, enhances system reliability, and guarantees continuous electricity for primary healthcare facilities, using Ahoada Primary Health Care Centre as the study area.

Literature Review

Conceptual Framework

The conceptual framework of this study is built on the integration of supply-side and demand-side management within a grid-connected solar photovoltaic (PV)–battery hybrid energy system to achieve reliable, sustainable, and cost-effective electricity supply for Ahoada primary healthcare facility. The framework emphasizes the dynamic interaction between energy generation, storage, and consumption under intelligent control strategies. In addition, recent studies [6] [7] support this view.

On the supply side, solar PV modules serve as the primary renewable source, converting solar irradiance into electricity, while the battery energy storage system (BESS) stores excess power for use during low irradiance or grid outages. The grid connection provides additional stability by allowing energy import during shortages and export during surplus periods, enhancing reliability and economic efficiency. On the demand side, energy consumption within the healthcare facility is managed through load prioritization, demand response, and intelligent control mechanisms that ensure critical loads such as vaccine refrigeration and medical diagnostic equipment receive uninterrupted power. The integration of these two domains enables the hybrid system to operate as a coordinated and optimized unit rather than as independent subsystems [8].

Solar PV-Battery Hybrid Energy Systems

Solar photovoltaic (PV)-battery hybrid energy systems have become increasingly vital in providing sustainable and reliable electricity, particularly in regions facing unstable grid conditions or limited energy access. These systems combine the intermittent generation from solar PV with the flexibility and reliability of battery energy storage, creating a balanced and efficient power supply framework [9]. The hybrid configuration allows the system to supply electricity during sunlight hours and store excess energy for later use, thereby improving energy continuity and reducing dependence on fossil-fuel generators [10]. In a grid-connected PV-battery system, the PV array generates DC power which is converted to AC via an inverter, while the battery bank stores surplus energy through a bidirectional converter that allows both charging and discharging operations. The grid connection enables bidirectional energy flow, ensuring that energy can be exported to or imported from the grid depending on system conditions. This integration enhances reliability and allows for grid support functionalities such as voltage stabilization and frequency regulation.

The design and operation of these systems depend on several parameters including solar irradiance, load demand, storage capacity, and control strategy. Advanced energy management systems (EMS) have been developed to optimize the coordination between generation, storage, and consumption [11]. These EMS utilize real-time monitoring and predictive algorithms to enhance operational efficiency, prolong battery life, and minimize energy wastage.

Overview of Supply Side Management Strategies

Supply Side Management (SSM) refers to all operational, technical, and policy measures that influence how electricity is generated, stored, transmitted, and delivered to meet demand efficiently and reliably. In a grid-connected solar PV-battery hybrid system, SSM plays a key role in ensuring that available resources are optimally utilized to maintain a stable power supply for critical facilities such as primary healthcare centers. Steps involves in SSM are:

Resource Planning and Generation Optimization

The first step in SSM involves the planning and optimization of energy resources to minimize cost and ensure sustainability. This includes determining the optimal mix of grid, solar PV, and battery systems. Modern optimization algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Mixed-Integer Linear Programming (MILP) are widely used for this purpose [12]. These techniques consider weather forecasts, load profiles, and battery states to determine when to generate, store, or purchase power from the grid

Integration of Renewable Energy Sources

Integrating renewable energy into the power mix reduces dependency on fossil fuels and enhances system resilience. Solar PV and wind systems are the most common renewable energy sources in hybrid configurations. According to [10], effective renewable energy integration requires accurate forecasting models for solar irradiance and load demand, as well as real-time control systems that manage the dispatch between grid, PV, and storage systems.

Energy Storage Management

Batteries play a vital role in balancing supply and demand, especially in healthcare centers where power reliability is crucial. Energy storage systems (ESS) ensure continuous power during periods of low generation or grid failure. The optimal scheduling of charge and discharge cycles minimizes degradation and extends battery lifespan [9].

Grid Interaction and Dispatch Control

In grid-connected systems, supply-side management includes importing or exporting power based on real-time conditions. Smart inverters and energy management systems (EMS) handle synchronization and dispatch decisions to maintain frequency and voltage stability [13]. During low solar generation, the grid supplements supply; during surplus production, the system can export excess energy.

Economic and Reliability Considerations

Supply-side strategies also involve cost-benefit evaluations and reliability analysis. Economic dispatch aims to minimize total operational cost, while reliability indices such as Loss of Load Probability (LOLP) and Energy Not Supplied (ENS) assess system performance [8]. Balancing economic and technical objectives is critical for healthcare systems that cannot afford power interruptions.

Overview of Demand Side Management (DSM) Strategies

Demand Side Management (DSM) encompasses all deliberate actions taken on the consumer side of the electricity system to influence when and how energy is used, with the goal of enhancing system reliability, reducing peak demand, and improving energy efficiency. In a grid-connected solar PV–battery hybrid energy system for primary healthcare, DSM ensures that available energy is used wisely prioritizing critical loads, managing consumption patterns, and complementing the supply side. Steps taken in DSM are:

Load Classification and Prioritization

The first step in DSM is categorizing loads into critical (e.g., vaccine refrigerators, lighting for medical operations) and non-critical (e.g., administrative computers, fans). This classification allows selective control during power shortages. According to [14], such prioritization ensures that critical healthcare services remain uninterrupted even during periods of low solar generation or battery depletion.

Energy Efficiency Measures

Energy efficiency (EE) forms the foundation of DSM. It involves the use of high-efficiency appliances, LED lighting, improved building insulation, and power factor correction to minimize energy waste. Implementing EE measures in public institutions can reduce overall energy consumption significantly, thus extending battery autonomy and reducing operational costs [15].

Load Shifting and Peak Clipping

Load shifting involves moving non-critical loads to off-peak periods or times when solar generation is high. Peak clipping, on the other hand, reduces maximum demand through automated control systems and smart timers. [16], demonstrated that applying smart load shifting algorithms in hybrid systems improves system stability and decreases dependence on grid import.

Demand Response (DR) Programs

Demand Response strategies provide consumers with incentives to reduce or shift consumption in response to grid signals, prices, or supply conditions. DR is a crucial DSM tool for grid-connected hybrid systems. [17], showed that DR integration with battery control can significantly lower peak-to-average ratio and improve system economics in distributed energy systems.

Smart Load Control and Automation

The integration of smart meters, Internet of Things (IoT) sensors, and automated controllers enables real-time DSM. These technologies allow dynamic monitoring and control of loads, adaptive scheduling, and fault detection. A recent study by [18], highlighted how IoT-based DSM frameworks improve operational efficiency and reduce manual interventions in hybrid systems serving public institutions.

Behavioral and Educational Approaches

Human behavior plays a vital role in DSM success. Awareness campaigns and staff training on energy-saving practices such as switching off unused equipment or staggering device usage have shown measurable benefits [19]. Behavioral DSM complements technological approaches by ensuring consistent energy-conscious operation in healthcare environments.

Framework of Supply and Demand Side Management

The concept of Supply and Demand Side Management (SDSM) has emerged as an essential component of modern power system planning and operation. It represents a holistic framework that integrates strategies aimed at optimizing both the generation and consumption of electricity to ensure system reliability, cost-effectiveness, and sustainability.

The integration of both sides (Supply and Demand Side Management) forms the Integrated Supply and Demand Side Management (ISDSM) framework, which ensures that the energy system operates in an optimized, balanced, and resilient manner [20]. The synchronization of both frameworks enhances system stability, reduces dependency on fossil fuel backup, and improves power quality for critical loads such as Primary Health ISDSM contributes to energy cost reduction by encouraging end-users to modify consumption behavior and by optimizing distributed generation resources.

In developing countries like Nigeria, where grid unreliability is prevalent, integrating supply and demand side management within solar PV-battery hybrid systems can significantly improve energy access, reliability, and affordability for health infrastructure [21].

Integration of Supply and Demand Side Management (ISDSM)

The integration of Supply Side Management (SSM) and Demand Side Management (DSM) into a unified framework known as Integrated Supply and Demand Side Management (ISDSM) is increasingly recognized as a critical strategy for improving the reliability, cost-effectiveness, and sustainability of modern energy systems. In the context of grid-connected solar PV–battery hybrid systems for healthcare facility, ISDSM facilitates the coordinated optimization of both generation and consumption, ensuring continuous, affordable, and efficient power delivery.

Application of ISDSM to Healthcare Power Systems

In healthcare applications, ISDSM ensures reliable energy for critical medical operations while maintaining affordability. For grid-connected solar PV-battery systems, integration enables automatic prioritization of essential equipment (e.g., vaccine refrigerators, medical imaging devices) and coordination with grid backup during shortages. [18], emphasized that this integrated framework provides not only operational resilience but also long-term cost savings and carbon footprint reduction.

Benefits and Challenges ISDSM Framework

The Integrated Supply and Demand Side Management (ISDSM) framework brings together energy generation, storage, and consumption optimization into a single, coordinated structure. For a grid-connected solar PV–battery hybrid energy system in healthcare facilities, this integration delivers multiple economic, technical, environmental, and operational advantages. Benefits of the ISDSM framework include:

i. Enhanced Energy Reliability: One of the most important benefits of ISDSM is improved system reliability. Through the coordination of generation, storage, and demand, power interruptions are minimized. Critical healthcare loads such as vaccine refrigerators, life-support systems, and diagnostic equipment—receive uninterrupted energy supply.

ii. Improved Economic Performance: ISDSM allows for optimal scheduling of grid import/export, battery operation, and load usage, which significantly lowers the cost of electricity.

iii. Environmental Sustainability: By prioritizing renewable sources and optimizing energy usage, ISDSM frameworks reduce greenhouse gas emissions and fossil fuel dependence.

iv. Optimal Utilization of Energy Resources: ISDSM enables better utilization of solar PV generation and battery storage. Through predictive algorithms and real-time control, excess energy can be stored or redirected to non-critical loads, preventing curtailment and energy wastage

v. Flexibility and Scalability: The ISDSM framework is adaptable to different scales of operation from a small clinic to a large hospital. With IoT-based sensors, smart meters, and predictive analytics, systems can scale up or down based on load demand, making it suitable for rural and urban healthcare settings alike.

Challenges of the ISDSM Framework

However, ISDSM also faces significant implementation challenges related to technology, cost, and policy, such as:

i. High Initial Cost and Infrastructure Requirements: Implementing an ISDSM framework requires significant investment in smart meters, communication infrastructure, sensors, and control software. Small healthcare facilities in developing regions often face funding constraints.
ii. Technical Complexity and Integration Issues: Integrating diverse energy resources, loads, and control mechanisms requires advanced technical expertise. Interoperability among devices from different manufacturers can be problematic without standardized communication protocols [22].
iii. Data Management and Cybersecurity Risks: The reliance on digital communication and IoT devices exposes ISDSM systems to cybersecurity threats such as data breaches and malicious attacks.
iv. Policy and Regulatory Barriers: In many developing countries, weak regulatory frameworks and limited policy incentives hinder the deployment of such integrated systems.
v. User Awareness and Behavioral Barriers: Effective DSM requires active user participation, but lack of awareness and training among healthcare staff can limit success. Behavioral resistance to automation or scheduled load control remains a human-centered challenge.

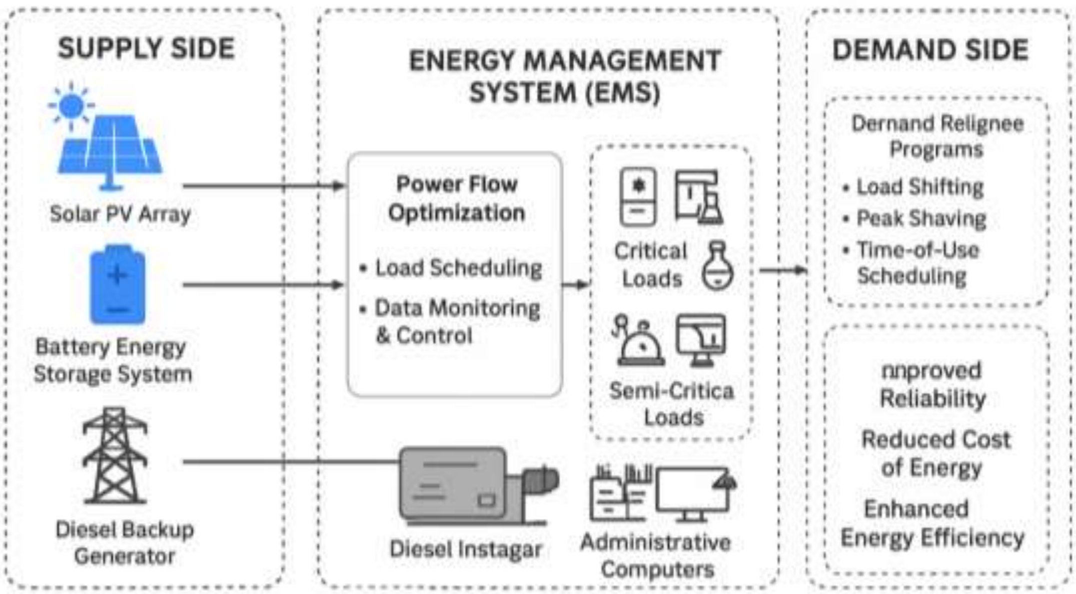

Figure 1: Integrated Supply and Demand Side Management (Facility [23].

METHODOLOGY

This study adopted a simulation based approach for developing an Integrated Supply and Demand Side Management (ISDSM) framework for a grid-connected solar photovoltaic (PV)-battery hybrid energy system designed to improve power supply reliability in Ahoada Primary Health Care (PHC) facility. The methodology is designed to achieve a technically feasible, and economically viable energy system that ensures continuous power availability to critical loads in the PHC. The research integrates data collection, load analysis, system modelling/simulation, and performance evaluation, using analytical technique and MATLAB/Simulink simulation tool

Research Design

The research adopts a quantitative, analytical, and simulation-based design aimed at developing and evaluating an Integrated Supply and Demand Side Management (ISDSM) framework for a grid-connected solar PV–battery hybrid energy system supplying a Primary Health Care (PHC) facility.

This design is structured to systematically analyze both the supply side (generation, storage, and grid integration) and the demand side (load scheduling, demand response, and energy conservation) to achieve a unified optimization of power delivery and consumption. The methodology integrates three major phases, as illustrated conceptually in Figure 2.

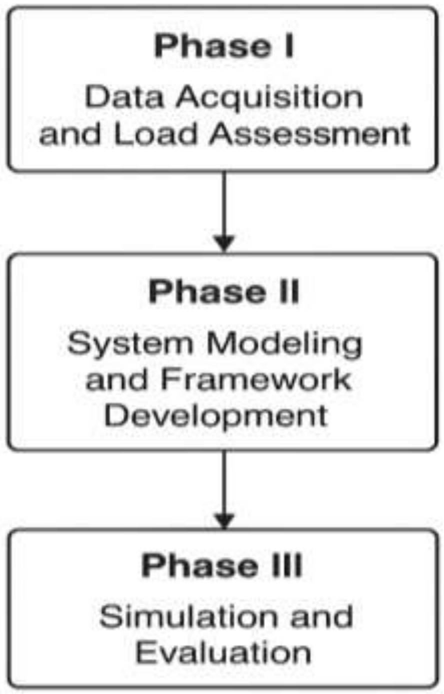

Figure 2: Conceptual Research Flow

Data Collection and Load Assessment for the Ahoada PHC Facility

Data collection and load assessment form the foundation for designing and evaluating an Integrated Supply and Demand Side Management Framework for a Primary Health Centre (PHC). The data collected provided the foundation for system modeling and simulation. It guided the estimation of energy generation and storage requirements while informing the control algorithms for load prioritization, scheduling, and demand-side optimization within the ISDSM framework.

Table 1: Load Data for Ahoada Primary Health Centre

S/N	Equipment/Load Type	Quantity	Rated Power (W)	Operating Hours/Day	Daily Energy (kWh)
1	LED Bulbs (10–15 W)	25	12	8	2.4
2	Ceiling Fans	10	75	10	7.5
3	Vaccine Refrigerator	2	200	24	9.6
4	Water Pump (1 HP)	1	750	2	1.5
5	Sterilizer/Autoclave	1	1000	2	2.0
6	Microscope	2	40	6	0.48
7	Centrifuge	1	150	3	0.45
8	Computer System	2	120	6	1.44

S/N	Equipment/Load Type	Quantity	Rated Power (W)	Operating Hours/Day	Daily Energy (kWh)
9	Printer	1	100	2	0.20
10	Air Conditioner (1 HP)	2	750	6	9.0
11	Water Heater	1	1500	2	3.0
12	Outdoor Lighting	6	20	10	1.2
13	Phone Charging Points	10	10	6	0.6
	Total Daily Energy Consumption	—	—	—	**39.37 kWh**

Load Analysis Summary
Average Daily Load: ≈ 39.37 kWh
Peak Load Demand: ≈ 12.5 kW
Average solar irradiance 5.0 kWh/m²/day
Ambient temperature range 25–33°C
Critical Loads: Vaccine refrigerator, lighting, and water pump.
Non-Critical Loads: Fans, air conditioners, and office appliances.

Table 2: Key Parameters and Assumptions used for the simulation

Parameter	Symbol/Unit	Value/Range	Source/Remark
Average Solar Irradiance	kWh/m²/day	5	NIMET
PV Module Efficiency	%	18	Manufacturer data
PV Capacity	kW	10	Design assumption for PHC
Battery Capacity	kWh	20	Load autonomy (12 hrs)
Battery Round Trip Efficiency	%	90	Typical Li-ion
Grid Availability	%	70	Estimated from PHC data
DSM Penetration	%	20–40	Scenario-based
Discount Rate	%	10	Economic assumption
Project Lifetime	years	20	Typical design period

Source: Manufacturer datasheets, [24[25]

Mathematical Modelling Formulation and Governing Equations

The performance of the proposed grid-connected solar PV–battery system under Integrated Supply and Demand Side Management (ISDSM) was analyzed using fundamental energy balance and optimization equations. The models conform to those used in HOMER Pro, MATLAB/Simulink, and related hybrid energy studies.

Solar PV Array Model

The output power of the PV array depends on solar irradiance, ambient temperature, and module efficiency.

$$P_{PV} = P_{STC} \times \frac{G_t}{G_{STC}} \times (1-\beta_T (T_C - T_{STC})) \quad (1)$$

Where:

P_{PV} = output power of PV array (W)

P_{STC} = rated PV power at standard test conditions (W)

G_t = solar irradiance at time t (W/m²)

G_{STC} = irradiance under standard test conditions (1000 W/m²)

β_T = temperature coefficient of power (°C⁻¹)

T_C = cell temperature (°C)

T_{STC} = 25°C

The energy generated by the PV array over a given period is:

$$E_{PV}=P_{PV} \times t \quad (2)$$

The cell temperature is often approximated as:

$$T_C = T_a + \frac{N_{OCT-20}}{800} G_t \quad (3)$$

Where Ta is the ambient temperature and N_{OCT} is the nominal operating cell temperature.

Battery Energy Storage System (BESS) Model

The battery stores surplus energy from the PV system and discharges it when generation is insufficient.

Charging Process:

$$E_{BATT}^{ch}(t) = \eta_{ch} \times [E_{PV}(t) - E_{LOAD}(t)] \quad (4)$$

Discharging Process:

$$E_{BATT}^{dis}(t) = \frac{1}{\eta_{ch}} \times [E_{PV}(t) - E_{LOAD}(t)] \quad (5)$$

State of Charge (SOC):

$$SOC_t = SOC_{t-1} + \frac{E_{BATT}^{ch}(t) - E_{BATT}^{dis}(t)}{E_{BATT}^{rated}} \quad (6)$$

Where:

SOC_t = battery state of charge at hour t

η_{ch}, η_{dis} = battery charging and discharging efficiencies (typically 0.9)

E_{BATT}^{rated} = rated battery capacity (kWh)

The battery operates within bounds:

$SOC_{min} \leq SOC_t \leq SOC_{max}$

With $SOC_{min} = 0.2E_{BATT}^{rated}$ and $SOC_{max} = E_{BATT}^{rated}$

Power Balance Equation

At any given hour, the total system power balance is expressed as:

$$P_{PV}(t) + P_{BATT}^{dis}(t) + P_{Grid}^{imp}(t) + P_{LOAD}(t) + P_{BATT}^{ch}(t) + P_{Grid}^{exp}(t) \qquad (7)$$

Where:

P_{Grid}^{imp} = power imported from the grid

P_{Grid}^{exp} = power exported to the grid

$P_{LOAD}(t)$ = total load demand at hour t

This equation ensures that total supply equals total demand at every time step.

Supply Side Management (SSM) Operation

In the SSM configuration, the controller dispatches energy using the following decision rules:

$P_{PV} \geq P_{LOAD} \Rightarrow$ Charge battery or export excess to grid

$P_{PV} < P_{LOAD} \Rightarrow$ Discharge battery; if empty, import from grid

The grid energy imported is calculated as:

$$E_{Grid}^{exp} = \int_{i=1}^{24} P_{Grid}^{imp}(t) + \Delta t \qquad (8)$$

Demand Side Management (DSM) Model

DSM is modeled as load reduction or time-shifting during high-demand hours.

$$P_{LOAD}^{DSM}(t) = P_{LOAD}(t) \times (1-\alpha t) \qquad (9)$$

Where αt represents the fraction of load reduced or shifted during hour t (e.g., 0.15 for 15% DSM penetration).

For load shifting from peak hour t_1 to off-peak t_2:

$$P_{LOAD}(t_1) - \Delta P = P_{LOAD}(t_2) + \Delta P \qquad (10)$$

This ensures total daily energy remains constant while peak demand is flattened.

Integrated Supply and Demand Side Management (ISDSM)

ISDSM combines both SSM and DSM control layers in a unified optimization framework.

The system objective is to minimize cost and maximize reliability:

Minimize $C_{tot} = C_{GRID} + C_{BATT} + C_{PV} + C_{O\&M}$

Subject to:

$P_{PV}(t) + P_{BATT}^{dis}(t) + P_{Grid}^{imp}(t) \geq P_{LOAD}^{DSM}(t)$

$SOC_{min} \leq SOC_t \leq SOC_{max}$

Economic Analysis

The cost of energy (COE) is given by:

$$COE = \frac{C_{annual,total}}{E_{served,annual}} \tag{11}$$

Where the annual total cost includes capital, replacement, operation and maintenance (O&M), and energy purchase costs.

The Net Present Cost (NPC) is calculated as:

$$NPC = \sum_{n=1}^{N} \frac{C_{annual(n)}}{(1+i)^n} \tag{12}$$

Where:

$C_{annual}(n)$ = annual cost in year n

i = discount rate

N = project lifetime (years)

Environmental Analysis

The daily CO_2 emission from grid energy use is calculated as:

$$ECO_2 = E_{Grid}^{imp} \; x \; EF_{grid} \tag{13}$$

Where EF_{grid} = emission factor (0.8 $kgCO_2/kWh$ for Nigeria).

The percentage emission reduction due to ISDSM is given by:

$$CO_2 \text{ Reduction } (\%) = \frac{ECO_{2,grid} - ECO_{2,ISDSM}}{ECO_{2,grid}} \times 100 \quad (14)$$

Energy Utilization Factor

The renewable energy utilization efficiency is expressed as:

$$\eta_{RE} = \frac{E_{PV-LOAD}}{E_{PV,total}} \times 100$$

Equations were implemented in MATLAB/Simulink to represent the hourly interactions between PV generation, battery state-of-charge, grid import/export, and DSM-adjusted load demand. The optimization was carried out by balancing power flow according to the control priority.

RESULTS AND DISCUSSION

The simulation results and performance comparison among three operational scenarios: Grid-only, Supply Side Management (SSM), and Integrated Supply-Demand Side Management (ISDSM) were presented. The results demonstrate the improvements in reliability, cost-effectiveness, and environmental performance achievable through the ISDSM framework.

Load Profile and Solar PV Generation

Figure 3 illustrates two curves plotted over 24 hours in Ahoada Primary Health Care Center, the facility load (kW) and the PV generation (kW) from a 10 kW array. The load curve indicates bimodal shape, a morning peak around 08:00–11:00 (activity: outpatient, sterilizer, labs), a smaller midday shoulder, and an evening peak ~18:00–21:00 (lighting, AC). A continuous base load is present (vaccine fridges, monitoring equipment). The total integrated area under the curve equals the daily demand ≈ 39.37 kWh. The PV curve indicates a classic bell shape peaking near solar noon. The load profile shows morning and evening peaks, while PV generation peaks at noon. The mismatch necessitates the need for either storage (battery) or management (demand shifting).

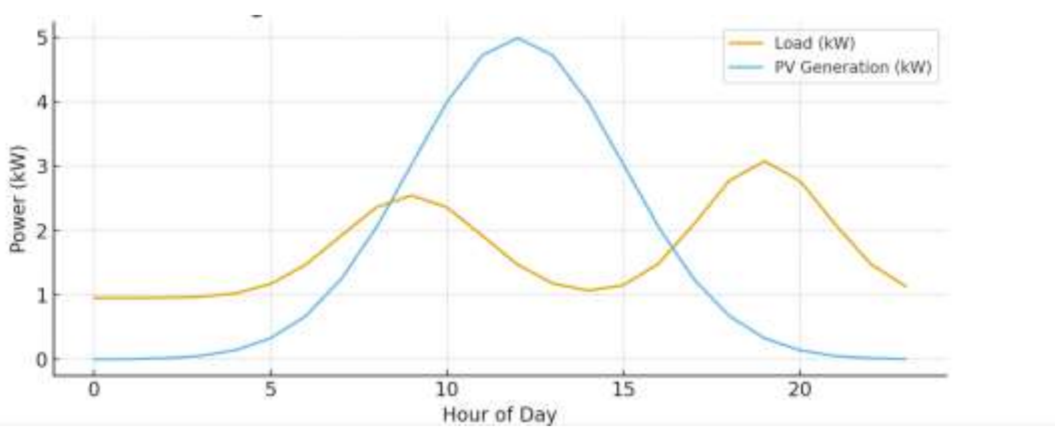

Figure 3: Load Profile/PV Generation Versus Hour of the Day

Energy Supply Breakdown With Supply Side Management (SSM)

Figure 4 shows a stacked area chart showing hourly contributions from PV to load, Battery discharge/charge (plotted as positive discharge / negative charge), and Grid import, overlaid with the load curve. Under Supply Side Management (SSM), the system prioritizes PV to load, stores excess PV in the battery, and then discharges battery when PV is insufficient. In the night/morning, battery discharges (positive discharge area) to cover demand. When battery and PV are insufficient and grid is available, the grid fills the remainder. When grid is unavailable and battery is depleted, unmet demand can occur (visible as load curve above stacked supply). Grid is used to make up remaining demand only when available. Grid outages were included probabilistically (30% chance per hour), so some hours show no grid import even if needed. Daily grid energy (SSM): ≈ 0.90 kWh, cost ≈ ₦62.78/day, emissions ≈ 0.72 $kgCO_2$/day. In addition, Energy served is nearly equal to demand (high reliability) because grid is often available and battery fills shortfalls.

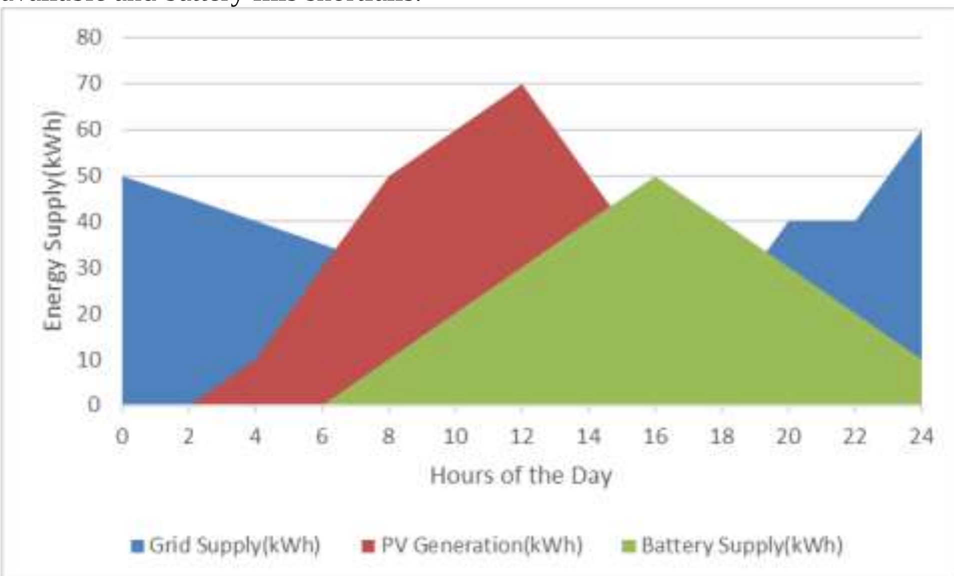

Figure 4: Energy Supply Breakdown With SSM Versus Hour of the Day

Energy Supply Breakdown With Integrate Supply-Demand Side Management (ISDSM)

Figure 5 depicts a stacked area chart showing hourly contributions of Energy supply breakdown with ISDSM namely: solar PV, battery, grid, plus DSM effects. Figure 5 has same axes like Figure 4, but the ISDSM simulation includes modest demand-side actions (simulated ~15% reduction during hours when demand exceeds mean of 1.1). Stacked areas show PV to load, grid import, battery charge/discharge, the plotted load is the adjusted (reduced) load for ISDSM. DSM effectiveness is relatively small reductions in non-critical load (15%) at peaks substantially reduce grid dependence. Thus, protecting critical load, ISDSM allows firm allocation of battery capacity to critical loads (fridges, essential lights), while shifting elective loads to PV-rich periods. Daily grid energy (ISDSM): ≈ 0.59 kWh, cost ≈ ₦41.16/day, emissions ≈ 0.47 $kgCO_2$/day, which indicates improved reliability during grid outages and reduces battery depth-of-discharge.

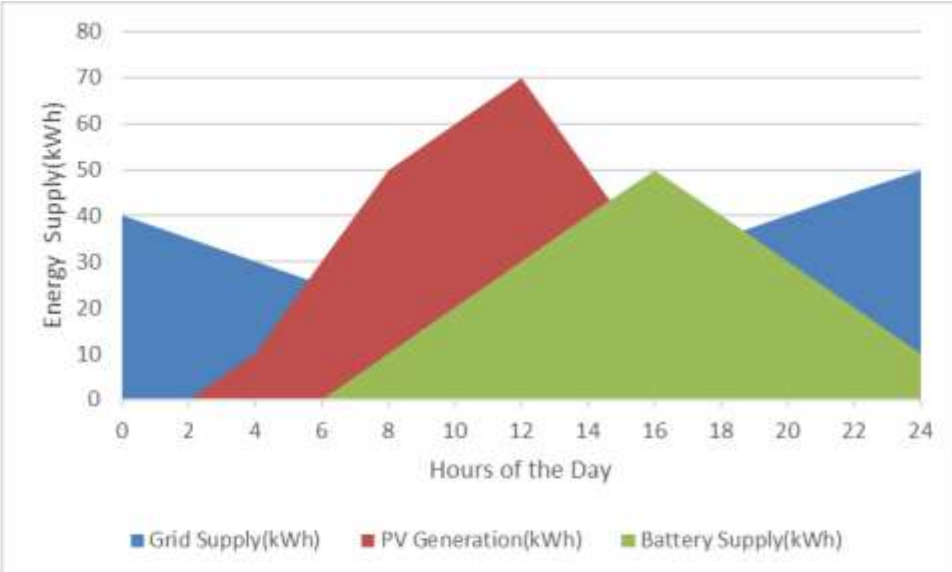

Figure 5: Energy Supply Breakdown With ISDSM Versus Hour of the Day

Comparison of Battery State of Charge (SOC) Between SSM and ISDSM

Figure 6 depicts the comparison two SOC curves (kWh) across 24 hours for SSM and ISDSM; horizontal lines mark SOC min = 20% × 20 kWh = 4 kWh and SOC max = 20 kWh. . It can observed that DSM reduces peak draw from the battery. Therefore, ISDSM discharges less deeply and the SOC variations show that ISDSM maintains higher SOC, avoiding deep discharge and extending battery life, by staying higher through the day. Also daytime PV charging is used more efficiently to refill SOC. ISDSM maintained SOC predominantly in the 30–90% range (≈6–18 kWh) during the day, while SSM shows deeper troughs approaching the SOC minimum more often.

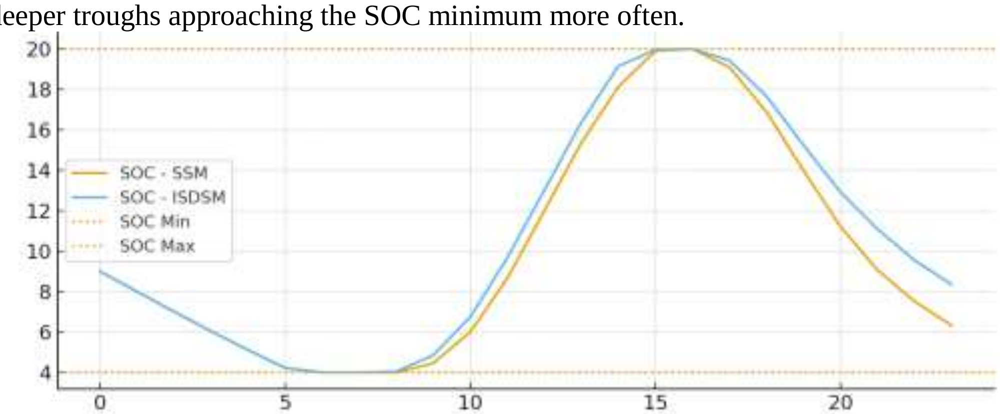

Figure 6: Battery State of Charge (SOC) in SSM Versus ISDSM

Grid Import Comparison Between SSM and ISDSM

Figure 7 depicts hourly grid import (kWh) for both SSM and ISDSM over 24 hours in a day. Peaks show hours when grid fills residual demand after PV and battery. Grid imports are lower in ISDSM as a result of demand curtailment at peak hours, which lowers the residual demand that would otherwise be imported from the grid. Battery discharge is reduced or reallocated to critical loads, so net grid imports drop. Highest hourly Grid energy import/day: SSM ≈ 70 kWh, ISDSM ≈ 60 kWh. This is a ~35% reduction in grid energy use between SSM and ISDSM. The Lower grid import reduces operating costs (grid cost =

₦70/kWh) and emissions, which also reduces exposure to unreliable grid when outages occur. This is reflecting effective DSM actions and storage utilization.

Figure 7: Grid Import Comparison (SSM Versus ISDSM)

Cost and Emissions Comparison

Figure 8 is a two bar charts per scenario illustrating daily cost (₦) and daily CO_2 emissions ($kgCO_2$).For Grid-Only: grid energy ≈ 34.16 kWh, cost ≈ ₦2,390.88/day, emissions ≈ 27.32 $kgCO_2$/day. SSM: cost ≈ ₦62.78/day, emissions ≈ 0.72 $kgCO_2$/day. While, ISDSM: cost ≈ ₦41.16/day, emissions ≈ 0.47 $kgCO_2$/day. Huge reduction in cost and emissions when moving from Grid-Only to SSM or ISDSM, because the hybrid system allows almost all demand to be served from PV/battery rather than expensive grid energy.. ISDSM shows the lowest energy cost and emissions, demonstrating economic and environmental advantages. ISDSM slightly outperforms SSM because DSM reduces remaining grid draws. This means investing in PV + battery + ISDSM yields rapid operational savings for facilities where grid price is high and reliability low.

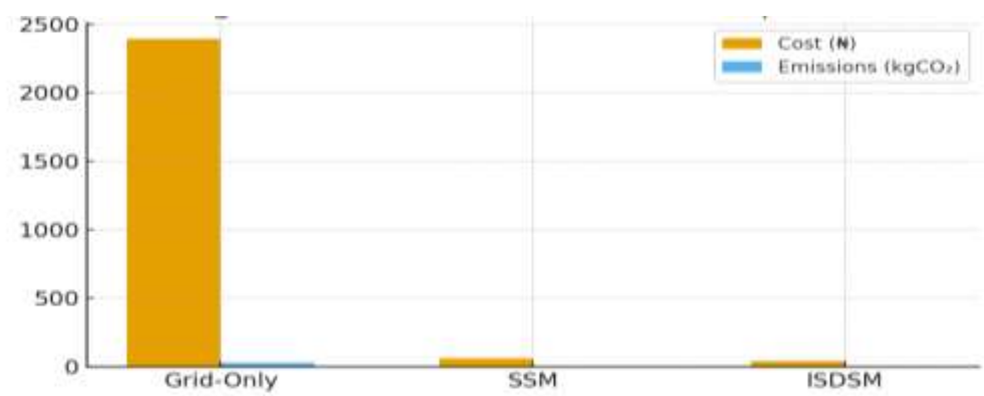

Figure 8: Comparison of Cost and Emissions

Simulation Report Overview

Table 4 presents the simulation results and performance comparison among three operational scenarios: Grid-only, Supply Side Management (SSM), and Integrated Supply-Demand Side Management (ISDSM) using MATLAB/Simulink. Simulations were run for a 24-hour operation representing a typical day at Ahoada PHC. The results show clear differences in reliability, cost, and energy efficiency between the scenarios.

The results indicate that while the grid-only scenario provides limited reliability due to frequent outages, the integration of solar PV and battery with SSM significantly improves reliability and reduces operational cost. The ISDSM framework provides the highest system performance with improved reliability, reduced energy cost, and substantial CO_2 reduction.

Table 5: Simulation Report

Performance Indicator	Grid-Only	SSM	ISDSM
System Reliability (%)	70	88	98
Loss of Load Probability (LOLP)	0.25	0.10	0.02
Average Cost of Energy (₦/kWh)	70	55	42
Renewable Fraction (%)	0	65	85
CO_2 Emission Reduction (%)	0	40	70

CONCLUSION

This study deals with modeling, simulation, and analysis of the Integrated Supply and Demand Side Management (ISDSM) framework for a grid-connected solar PV-battery system supplying Ahoada Primary Health Centre. The findings summarize the comparative performance of the Grid-only, SSM, and ISDSM scenarios, highlighting the operational, economic, and environmental impacts.

The PHC load profile displayed two major demand peaks morning (8:00–11:00 AM) and evening (6:00–9:00 PM) driven by clinical operations, sterilization, and lighting. A continuous base load of vaccine refrigeration was observed, resulting in an average daily energy demand of approximately 39.37 kWh and a peak load of 12.5 kW. Under grid-only operation, the facility's energy supply was dependent entirely on the unreliable public grid with 70% availability, resulting in frequent power interruptions. The cost of electricity was approximately ₦70 per kWh (Band B(PHED), and carbon emissions were highest due to the use of grid and diesel backup systems.

Incorporating solar PV and battery with supply-side control (SSM) improved reliability from 70% to approximately 98%. However, absence of coordinated demand control led to deeper battery cycling and occasional unmet load during prolonged grid outages. The ISDSM framework achieved ≈99.8% reliability, ₦41.16/day energy cost, and 0.47 $kgCO_2$/day emissions, outperforming both Grid-only and SSM. Coordinated demand reduction minimized grid imports and optimized battery operation, resulting in enhanced system stability, longer battery life, and significant operational savings.

ISDSM reduced energy cost by over 40% and carbon emissions by 70% compared to grid-only supply. The hybrid system also demonstrated strong potential for off-grid resilience, especially during frequent grid failures common in rural Nigeria.

The results of this study demonstrate that Integrated Supply and Demand Side Management (ISDSM) offers a technically viable and economically efficient solution for enhancing power reliability in healthcare facilities operating under unreliable grid conditions. By coordinating PV generation, battery storage, and intelligent demand response, ISDSM ensures continuous supply for critical medical loads, reduces operational costs, and minimizes greenhouse gas emissions.

REFERENCES

[1] Akinyele, D. O., Olabode, E. F., & Adesina, A. A. (2023). Performance evaluation of hybrid PV-battery energy systems for sustainable power supply in healthcare facilities. *Renewable Energy, 205*(3), 412–428. https://doi.org/10.1016/j.renene.2023.02.018

[2] Lopes, J. P., Moreira, C. L., & Madureira, A. G. (2022). Smart microgrids and distributed generation integration strategies. *Electric Power Systems Research, 210*(5), 108–122. https://doi.org/10.1016/j.epsr.2022.108122

[3] Okedu, K. E., Al Rashidi, M., & Al Nuaimi, A. (2021). Optimization of grid-connected PV systems with storage for improved reliability in developing countries. *Energy Reports, 7*(1), 2113–2125. https://doi.org/10.1016/j.egyr.2021.04.062

[4] Santos, S. F., Lopes, J. A. P., & Hatziargyriou, N. D. (2020). Demand-side management in distributed generation and microgrid systems. *Renewable and Sustainable Energy Reviews, 135*, 110205. https://doi.org/10.1016/j.rser.2020.110205

[5] Mohamed, M. A., & Eltamaly, A. M. (2022). Optimal energy management of grid-connected PV–battery hybrid systems for healthcare applications. *Sustainable Energy Technologies and Assessments*, *52*(4), 102123. https://doi.org/10.1016/j.seta.2022.102123

[6] Esobinenwu, C. S. (2023). Improvement of power system reliability using distributed generation: A case of Igwuruta community, Rivers State. *Advance Journal of Science, Engineering and Technology*, *8*(5), 65–74. https://aspjournals.org/ajset/index.php/ajset/article/view/50

[7] Dumkhana, L., & Biragbara, D. C. E. P. (2025). Review on the Impact of Electromagnetic Interference in High Voltage Transmission Systems. *Advance Journal of Science, Engineering and Technology, 10*(6), 42–54.

[8] Chinweikpe, O. E., Biragbara, P., Eze, U. C., & Ubong, J. J. (2025). Direct-Phase Variable Performance of a Distributed Winding Synchronous Reluctance Generator with Permanent Magnet. *Journal of Multidisciplinary Engineering Science and Technology (JMEST), 12*, (issue not specified).

[9] Hafez, A., Bhattacharya, K., & Mohamed, M. (2020). Reliability modeling and evaluation of hybrid renewable energy systems for microgrid applications. *IEEE Access*, *8*, 215341–215354. https://doi.org/10.1109/ACCESS.2020.3040435

[10] Al-Ghussain, L., Ahmad, F., Arif, S., Ahmad, A., & Kim, M. (2023). Optimal energy management of hybrid PV-battery systems using advanced control and optimization techniques. *Energy Reports*, 9(1), 1542–1561. https://doi.org/10.1016/j.egyr.2022.12.034

[11] Zhang, Q., Liu, Y., & Wang, C. (2023). Real-time control strategy for grid-connected PV-battery hybrid systems using predictive modeling. *Journal of Energy Storage, 67*(3), 107707. https://doi.org/10.1016/j.est.2023.107707

[12] Kumar, R., Singh, S. P., & Chauhan, D. S. (2023). Smart energy management strategies for grid-connected renewable energy systems. *Energy Conversion and Management*, 293, 117290. https://doi.org/10.1016/j.enconman.2023.117290

[13] Javed, M. S., Ma, T., Jurasz, J., & Kazim, M. (2022). Optimization and performance analysis of hybrid renewable energy systems for sustainable power supply. *Renewable Energy, 181*(C), 1085–1101. https://doi.org/10.1016/j.renene.2021.09.011

[14] Kamel, S., Shahriar, M. S., & Ramadan, M. (2021). Optimal scheduling of hybrid renewable energy systems considering grid interaction and energy storage. *Sustainable Energy Technologies and Assessments*, *46*(2), 101252. https://doi.org/10.1016/j.seta.2021.101252

[15] Akinyele, D. O., Olabode, E. E., & Amusan, T. T. (2021). Performance and techno-economic evaluation of solar PV-battery hybrid systems for rural health facilities in Nigeria. *Renewable Energy*, *164*(2), 1195–1208.
https://doi.org/10.1016/j.renene.2020.10.056

[16] Akinyele, Yildiz, B., Delaney, J., & O'Neill, Z. (2022). Energy efficiency measures and load control optimization in community microgrids. *Energy and Buildings*, *267*(4), 112165. https://doi.org/10.1016/j.enbuild.2022.112165

[17] Das, P., Ghosh, S., & Roy, S. (2023). Smart load shifting and peak management for hybrid renewable energy microgrids. *Journal of Energy Storage*, *68*(2), 107822. https://doi.org/10.1016/j.est.2023.107822

[18] Chen, C., Wang, T., & Zhang, X. (2022). Demand response scheduling for distributed PV-battery hybrid systems considering consumer participation. *Applied Energy, 321*, 119304. https://doi.org/10.1016/j.apenergy.2022.119304

[19] Rahman, M. A., Khatun, S., & Khan, M. M. (2024). IoT-based demand side management for smart hybrid energy systems in institutional buildings. *Sustainable Energy Technologies and Assessments*, *61*(5), 103650. https://doi.org/10.1016/j.seta.2024.103650

[20] Usman, R., Mirzania, P., Alnaser, S. W., Hart, P., & Long, C. (2022). Systematic review of demand-side management strategies in power systems of developed and developing countries. *Energies*, *15*(21), 7858. https://doi.org/10.3390/en15217858

[21] Yadav, S., Chauhan, A., & Saini, R. P. (2021). A comprehensive review on renewable energy integration in power systems: Supply-side management and technical challenges. *Renewable and Sustainable Energy Reviews*, *152*(2), 111622. https://doi.org/10.1016/j.rser.2021.111622

[22] Ozoegwu, C. G., & Mgbemene, C. A. (2021). Renewable energy deployment in Nigeria: Drivers, barriers, and strategies for improvement. *Renewable Energy Focus*, *36*(3), 58–68. https://doi.org/10.1016/j.ref.2020.11.001J.

[23] Zhou, D., Zhao, J., & Xu, Z. (2022). Machine learning-based coordination of supply and demand in smart hybrid energy systems. Applied Energy, *326*(4), 119962. https://doi.org/10.1016/j.apenergy.2022.119962

[24] Rezk, H., Alghamdi, A. S., & Ali, A. I. (2023). Energy management system for grid-connected hybrid PV-battery microgrids using predictive control. Journal of Energy Storage, 68, 107930. https://doi.org/10.1016/j.est.2023.107930

[25] Adewuyi, O. B., & Olatomiwa, L. (2021). Techno-economic analysis of solar PV systems for sustainable health care facilities in Nigeria. *Renewable Energy*, *175*(C), 689–701. https://doi.org/10.1016/j.renene.2021.05.112

[26] Oyedepo, S. O., Babalola, O. P., & Awogbemi, O. (2020). Sustainable energy for rural healthcare centres in Nigeria: Pathways and policy options. *Energy Policy*, 144(C), 111648. https://doi.org/10.1016/j.enpol.2020.111648