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Hybridization of Renewable Energy for Economic Viability in Salvation Ministries Cathedral Power Network

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Abstract
This study undertakes a rigorous techno-economic and environmental evaluation of hybrid renewable energy systems as a pathway to improving electricity supply in Salvation Ministries Cathedral, Igwuruta, Rivers State, Nigeria, an area typified by acute rural energy deficits. Drawing upon high-resolution meteorological datasets from NASA and the Global Wind Atlas, the analysis examines the viability of an integrated system comprising solar photovoltaics, wind energy, battery storage, and diesel generation within an optimized microgrid framework. Advanced modeling platforms including HOMER Pro for economic optimization and ETAP 19.0.1 for transient electrical performance are employed to simulate alternative configurations under representative load conditions and climatic realities. Wind resource characterization leverages Weibull probability distributions and power law extrapolation, while the financial analysis considers Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), and payback horizons benchmarked against prevailing Nigerian market indices and the MYTO 2022 tariff structure. The results indicate that a PV-Wind-Battery-Diesel hybrid architecture achieves a low LCOE of N54.6/kWh and reduced operational expenditure, while delivering substantial emission reductions of over 10,045 metric tons of CO2 annually relative to diesel-only baselines. The system demonstrates a favorable payback period of 2.25 years and a return on investment of 39.1%, establishing strong financial viability. The findings affirm the strategic role of decentralized hybrid microgrids in advancing rural electrification and provide actionable insights for policymakers, investors, and regulators navigating sub-Saharan Africa's dynamic energy transition.
Keywords-*Hybrid renewable energy, Microgrid, Solar PV, Wind turbine, Techno-economic analysis, HOMER Pro, ETAP, Net Present Cost, Levelized Cost of Energy, Weibull distribution, Grid integration, Distributed generation*

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I. INTRODUCTION

Nigeria's energy sector faces significant challenges, including inadequate generation capacity, aging infrastructure, and frequent grid failures. These issues result in economic losses estimated at $29 billion annually due to power shortages and blackouts. The national grid, heavily reliant on gas-fired plants and hydroelectric stations, often fails to meet the demands of the country's over 200 million population. As of 2023, Nigeria boasts an installed electricity generation capacity of approximately 12,643 MW; however, actual power generation often falls significantly short of this capacity, with the country producing only about 4,211 MW in the third quarter of 2023, representing roughly 33% utilization of installed capacity.

The transmission and distribution segments of Nigeria's power sector are plagued by aging infrastructure and high technical losses. Many transmission lines and substations are over 40 years old, leading to frequent breakdowns and inefficiencies. These infrastructural deficits contribute to the sector's inability to deliver consistent power supply, with the national grid experiencing multiple collapses annually[18]. For instance, in April 2024, Nigeria suffered its fifth grid collapse of the year, reducing power supply from 4,020 MW to around 50 MW.

In response to these challenges, hybrid renewable energy systems (HRES) have emerged as a viable solution, particularly for rural and off-grid areas. Studies have demonstrated the technical and economic feasibility of HRES configurations, such as photovoltaic (PV)/wind/battery/diesel systems, in providing reliable electricity supply. For instance, an optimized HRES in Fanisau, Northern Nigeria, achieved a cost of energy of $0.25/kWh and significant reductions in carbon emissions[3]. Moreover, integrating renewable energy into the national grid presents opportunities to enhance grid stability and capacity[10]. However, high levels of renewable penetration can lead to frequency and voltage fluctuations, necessitating strategic investments in energy storage and advanced control systems.

The Salvation Ministries' Cathedral Project (SMCP) as shown in Figure 1, is a 56,130 square meter structure with a seating capacity of 120,000, making it one of the world's largest church auditoriums. Located in Igwuruta, Rivers State, Nigeria, it serves as a central hub for religious services, community gatherings, and media broadcasts. Its electrical distribution system, estimated to have a peak demand of 10-20 MW, powers extensive lighting, HVAC systems, sound systems, and other critical loads. The cathedral likely connects to the grid at 33 kV, with transformers stepping down to 415 V, supplemented by diesel generators and uninterruptible power supplies (UPS) for critical loads.

The cathedral exemplifies the broader energy challenges faced by large religious institutions in Nigeria, where unreliable electricity supply from the national grid disrupts services, escalates operational costs through heavy reliance on diesel generators, and hinders economic sustainability. Frequent grid collapses, driven by aging infrastructure, vandalism, and insufficient generation capacity, force such facilities to operate generators for extended periods, resulting in prohibitive fuel expenses (often exceeding millions of naira annually) and environmental pollution from emissions. This dependency not only strains the cathedral's budget but also exposes it to volatile diesel prices amid Nigeria's economic pressures.

This research proposes an optimization of hybrid renewable energy integration for enhanced grid capacity and economic viability in SMCP, Rivers State, Nigeria. The study aims at reducing the high cost of running the existing fossil fuel and diesel means of power generation while providing an improved alternative power supply with minimal greenhouse gas emissions. The specific objectives include: (1) Collating wind power density, wind energy density, solar irradiance, and solar radiation data using appropriate instruments and validated models; (2) Evaluating the single line diagram of SMCP power network; (3) Studying the load flow of SMCP distribution network using ETAP; (4) Designing and simulating hybrid renewable energy models combining wind and solar power generation using ETAP version 19.0.1; and (5) Performing detailed economic analysis including calculation of optimized cost savings using Net Present Value as the primary metric.

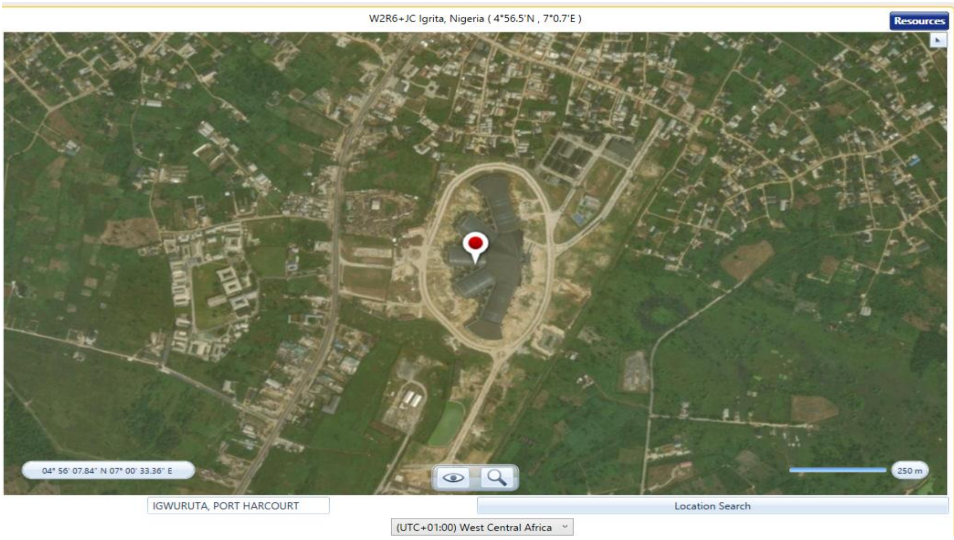

Fig1: Location coordinates of SMCP (Src: Homer)

II. DEFINITION OF KEY TERMINOLOGIES

A. Hybrid Renewable Energy System (HRES)

A Hybrid Renewable Energy System (HRES) integrates multiple renewable energy sources such as solar photovoltaic (PV), wind turbines, biomass, and hydropower with energy storage solutions and backup generators to provide reliable and sustainable electricity[6]. These systems are designed to capitalize on the complementary characteristics of different renewable energy sources, providing a more consistent and reliable power supply. HRES configurations can be broadly categorized as grid-connected, off-grid standalone, or hybrid configurations combining multiple sources. Key components include renewable energy generators, energy storage systems (typically batteries), backup generators, and power electronics with control systems.

B. Net Present Cost (NPC)

The Net Present Cost (NPC) represents the total cost of installing and operating a system over its lifetime, discounted to present value. It includes all capital, replacement, maintenance, and operational costs. Lower NPC values indicate more economically favorable systems[13]. The NPC is calculated using the formula:

$$NPC = C_0 + \Sigma(Ct / (1+r)^t) \text{ for } t = 1 \text{ to } n$$

Where C_0 is the initial investment, Ct is the cash flow at time t, r is the discount rate, and n is the project lifetime in years. This fundamental concept determines the value of a series of cash flows by discounting future cash flows back to their present value.

C. Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) represents the average cost per kilowatt-hour (kWh) of electricity generated over the system's lifetime[12]. It encompasses capital expenditures, operation and maintenance costs, fuel expenses, and replacement costs. The LCOE allows for fair comparison between different energy options and is calculated as:

$$LCOE = (C_0 + \Sigma(OMt + Ft) / (1+r)^t) / \Sigma(Et / (1+r)^t)$$

Where OMt represents operation and maintenance costs, Ft represents fuel costs, and Et represents energy production in year t.

D. Weibull Distribution

The Weibull probability distribution function is widely used for wind speed characterization and prediction in wind energy assessments[8]. The two-parameter Weibull distribution is given by:

$$f(v) = (k/c) \times (v/c)^{(k-1)} \times \exp(-(v/c)^k)$$

Where k is the dimensionless shape parameter, c is the scale parameter in m/s, and v is the wind speed in m/s. The shape parameter k indicates the wind speed distribution pattern: when $k = 2$, the distribution becomes the Rayleigh distribution; when $k < 2$, the distribution has a heavy tail; and when $k > 2$, the distribution approaches a normal distribution.

E. Wind Power Density (WPD)

Wind Power Density is an indicator that demonstrates the capacity of wind resources at a specific site[9]. It describes the amount of energy generated by different wind speeds at a particular location and is calculated from the Weibull distribution parameters as:

$$WPD = 0.5 \times \rho \times c^3 \times \Gamma(1+3/k)$$

Where ρ is the air density (1.225 kg/m³ at sea level), c is the scale parameter, and Γ is the gamma function. Wind power density classifications range from Class 1 (poor, <100 W/m²) to Class 7 (outstanding, >800 W/m²).

F. Capacity Factor

The capacity factor is an indicator used to evaluate how well wind turbines are performing. It is the relationship between the maximum rated power of the wind turbine and the total average power that the turbine produces over a specific period. The annual capacity factor is given by:

$$CF = Pe,Ave / Pe,R = (1/T) \times \int P(v) \times f(v)\, dv$$

Where Pe,Ave is the average output power, Pe,R is the rated power, P(v) is the power curve function, and f(v) is the wind speed probability density function.

G. Power Law for Wind Speed Extrapolation

Wind speed determination at various hub heights is performed using the power law, which is expressed as:

$$V_2 = V_1 \times (Z_2/Z_1)^\alpha$$

Where V_2 and V_1 are wind speeds at heights Z_2 and Z_1 respectively, and α is the wind shear exponent. Typical values of α range from 0.10 for smooth water surfaces to 0.40-0.50 for forests or very rough terrain. For open rural terrain, $\alpha = 0.14$ is commonly used.

III. LITERATURE REVIEW

A. Overview of Nigeria's Power Sector

Nigeria's power sector, despite being Africa's largest economy, continues to grapple with significant challenges that hinder its ability to provide reliable and adequate electricity to its over 200 million citizens. The sector is characterized by underutilized generation capacity, frequent grid collapses, infrastructural deficits, and regulatory inefficiencies[10]. The transmission and distribution segments are plagued by aging infrastructure and high technical losses, with many transmission lines and substations being over 40 years old.

Financial instability is a significant issue in Nigeria's power sector. The government has historically subsidized electricity tariffs, leading to a tariff shortfall of approximately 3 trillion naira. In an attempt to alleviate fiscal pressure, the government implemented a targeted tariff hike for high-usage consumers in 2024, resulting in a 35% reduction in electricity subsidies. Despite these measures, the sector still faces a crippling debt load, with unpaid debts to power generating companies amounting to 4 trillion naira ($2.5 billion).

The Nigerian Electricity Regulatory Commission (NERC), established in 2005, serves as the primary regulatory body overseeing the country's electricity sector[11]. In a significant policy shift, the Electricity Act of 2023 was enacted to decentralize the power sector, allowing states to establish their electricity markets and regulatory agencies. This reform aims to improve energy access and supply by enabling states to explore innovative mechanisms and attract investments for large-scale projects[18].

B. Renewable Energy Potential in Nigeria

Nigeria is endowed with abundant renewable energy resources. The country receives an average solar radiation of about 5.5 kWh/m²/day, with an estimated potential of 427,000 MW of solar power (Fig2a). This vast potential remains largely untapped, with solar energy contributing minimally to the national grid. Initiatives like the Nigeria Renewable Energy Master Plan aim to increase solar energy's share in electricity generation[10], targeting 500 MW by 2030.

Wind energy potential (Fig2b) is moderate, with average wind speeds ranging from 2.0 to 4.0 m/s at 10 meters above ground level. Higher wind speeds are observed in the northern regions, particularly in Sokoto, Kano, and Maiduguri, making these areas suitable for wind energy development[3]. The estimated wind energy potential is about 10,000 MW, yet it remains underutilized due to inadequate infrastructure and investment.

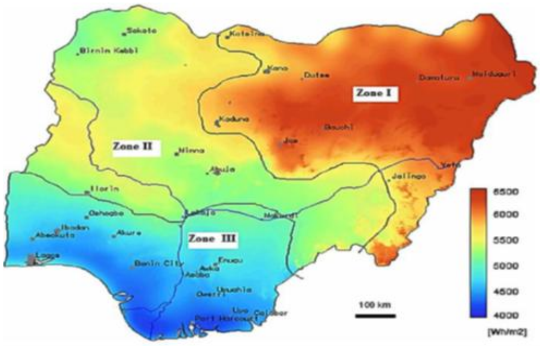

Fig 2a&b: (a) Nigeria's Solar Resource Map (Availableonline http://dx.doi.org/10.1016/j.rser.2015.03.098) (b) the Nigerian Wind Resource Map (Available Online http://dx.doi.org/10.4236/sgre.2014.59021)

Hydropower is currently the most utilized renewable energy source in Nigeria, contributing approximately 17% to the national electricity supply. The country has an estimated hydropower potential of 14,750 MW, comprising 11,250 MW from large hydropower and 3,500 MW from small hydropower sources. Despite this, only about 2,000 MW has been developed, indicating significant room for expansion.

C. Previous Studies on HRES in Nigeria

Several researchers have analyzed hybrid renewable energy systems in Nigeria with varying configurations and applications. Analysis and review of wind speed data for Port Harcourt was done using the Weibull probability distribution function to determine the feasibility of wind power generation[1]. The research found that while low-level wind speeds were moderate, the estimated wind speed potential dramatically increased with height. By projecting the wind speed using the logarithmic profile equation, the optimum average wind velocity at an altitude of 50 meters was calculated to be 17.75 m/s, corresponding to an optimal power density of 1370.13 W/m².

A review of the utilization of HOMER software to simulate and compare the energy cost and performance of a Solar PV/Diesel hybrid system was done against a generator-only system across various load profiles in Nigeria[2]. The results showed that the optimal hybrid configuration achieved a superior Levelized Cost of Energy (LCOE) range of USD 0.156/kWh to 0.172/kWh, significantly lower than the USD 0.30/kWh average LCOE for diesel-only systems. The system delivered operational expenditure savings on fuel ranging from 41.68% to 47%.

Optimal sizing and techno-economic analysis of hybrid renewable energy systems, specifically a photovoltaic/wind/battery/diesel system in Fanisau, Northern Nigeria was carryout[3]. The study achieved a COE of $0.25/kWh, demonstrating the economic competitiveness of hybrid systems in the region. Amadi et al. (2023) carried out research evaluating the comparative cost analysis between a standalone solar PV system and a diesel generator for a commercial load in Port Harcourt, strongly advocating for the adoption of solar PV as the primary sustainable and cost-effective power source[16][17].

D. Grid Integration Challenges and Solutions

The integration of renewable energy sources into existing power grids presents several technical challenges[4]. Variability and intermittency of renewable sources such as solar and wind can destabilize the power system by causing frequent mismatches between electricity supply and demand. Voltage and frequency control become critical issues as conventional grids were designed around large centralized power stations that inherently contribute to voltage and frequency regulation, while RES-based systems lack inertia and reactive power capability.

Grid support technologies for renewable energy integration include Energy Storage Systems (ESS) such as lithium-ion batteries and pumped hydro storage, which buffer the mismatch between energy supply and demand. Smart grid technologies integrate digital communication, sensors, and advanced control mechanisms to improve monitoring and management. Flexible AC Transmission Systems (FACTS) devices such as SVC and STATCOM enhance grid stability by regulating voltage and improving power transfer capability.

E. Research Gap

Although substantial research has been conducted on hybrid renewable energy systems in Nigeria, the majority of existing studies have concentrated on techno-economic optimization, sizing, and performance evaluation of isolated or off-grid configurations, with limited attention to grid-integrated applications and optimal placement within distribution networks. For example, a project to optimized a hybrid solar PV-wind-diesel-battery system using HOMER software for a remote medical center was carried out[14]; however, their analysis was limited to a single isolated load and did not examine integration into the utility distribution network.

Resource assessment studies provided valuable wind speed data and Weibull-based potential estimates specifically for Port Harcourt in Rivers State[1], yet these studies stopped at resource characterization and did not extend to hybrid system design, economic viability, or practical grid integration strategies. Consequently, critical gaps persist regarding: (1) the combined utilization of wind and solar resources in Rivers State within an existing distribution network; (2) the impact of optimal upstream placement of renewable generators on system stability, load balancing, and fault reduction; and (3) the comprehensive economic evaluation of such grid-enhanced hybrid configurations using metrics such as Net Present Value (NPV). This study bridges these gaps by assessing wind and solar availability in Rivers State and proposing a hybridized renewable energy system with strategic integration into the network.

IV. MATERIALS AND METHODS

A. Study Area Description

The Salvation Ministries' Cathedral Project is located in Igwuruta, Rivers State, Nigeria (Latitude 4.97°N, Longitude 7.01°E, Elevation 20m). Igwuruta is a major town within the Ikwerre Local Government Area of Rivers State. The facility has an estimated peak demand of 10-16 MW, with an average daily energy consumption of approximately 46 MWh/day. The electrical distribution system connects to the grid at 33 kV through Port Harcourt Electricity Distribution Company (PHEDC), with transformers stepping down to 415 V, supplemented by diesel generators for backup power during grid outages.

The cathedral's electrical infrastructure includes multiple generator sets (GT-01 to GT-05), step-down transformers (TR-800, TR-801 at 33/11kV, 7.5MVA), distribution transformers (TR-701 to TR-706 at 11/0.415kV, 2.0-2.5MVA), and various load centers including lighting, HVAC, sound systems, and other auxiliary loads (Fig3a). The single-line diagram of the SMCP power network was evaluated to understand the existing configuration and identify optimal integration points for renewable energy sources.

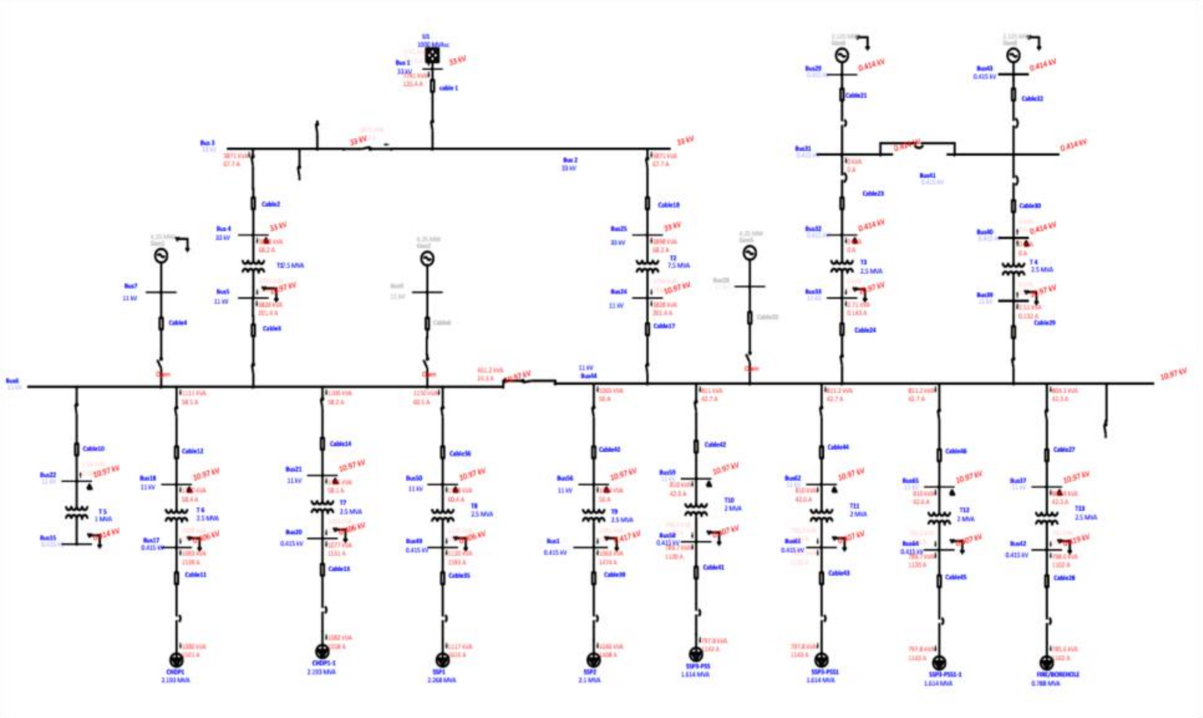

Fig3a: Load flow Analysis of the SMCP Distribution System without HRES

B. Data Collection and Sources

The study utilized multiple data sources as summarized in Table I:

- Solar radiation data: Global Horizontal Irradiance (GHI) and ambient temperature from NASA POWER database for PV system sizing and seasonal performance modeling
- Wind speed data: Average wind speed at 10m and 100m heights from Global Wind Atlas and NASA for feasibility assessment of wind energy inclusion
- Load demand data: Hourly/daily load profiles from PHED reports, smart meter data under NERC Meter Asset Provider Program, and field surveys
- Electricity tariffs: NERC Multi-Year Tariff Order (MYTO 2022) ranging from N32 to N65/kWh depending on customer class
- Diesel fuel cost: Average market price of N1,200-1,500/litre from PPPRA and local filling station surveys
- Renewable component costs: Solar panels, inverters, batteries from local vendors (Rubitec, Jumia), Alibaba, and IRENA benchmarks
- Financial parameters: Discount rate (25.4%), inflation rate (15.2%), and project lifetime (25 years) from CBN reports and World Bank guidelines

TABLE I: Climate Data for Igwuruta, Rivers State, Nigeria

Parameter	Unit	Value
Latitude	°N	4.97
Longitude	°E	7.01
Elevation	m	20
Heating Design Temperature	°C	18.0
Cooling Design Temperature	°C	33.3
Average Daily Solar Irradiance	kWh/m²/day	4.53
Average Wind Speed @ 100m	m/s	3.92
Annual Average Temperature	°C	26.8
Annual Relative Humidity	%	84.3

C. Solar Resource Assessment

Igwuruta, Rivers State benefits from its equatorial location, receiving consistently high levels of solar radiation throughout the year. The average daily solar irradiance ranges from 3.5 to 6.3 kWh/m²/day, with an annual average of approximately 4.53 kWh/m²/day. From Fig 3b, Peak solar months occur between January and April, with irradiance levels above 5.5 kWh/m²/day, while June to September shows relatively lower values (around 3.5-4.1 kWh/m²/day) due to overcast conditions in the rainy season. The clearness index varies from 0.3 to 0.7, indicating moderate to high solar visibility, especially during the dry season.

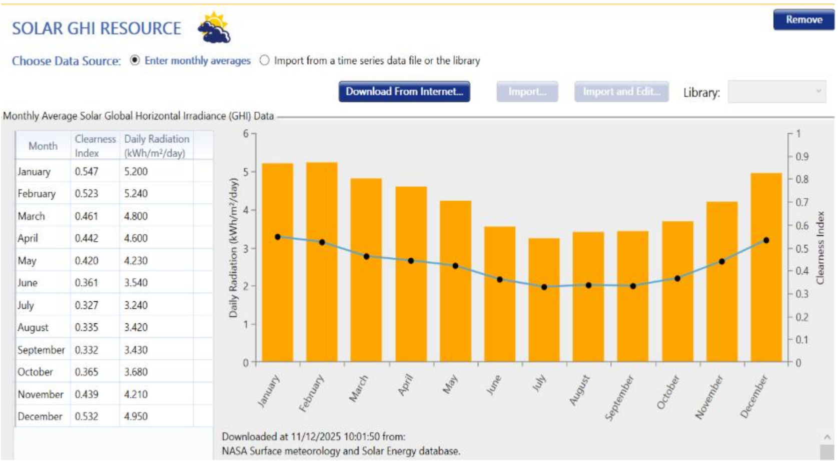

Fig3b: Monthly average solar irradiance of Igwuruta, Rivers State (kWh/m²/day) (src: Homer)

The PV system DC power output is calculated using the equation:

$$PDC = Gt \times A \times \eta STC \times [1 - \gamma(Tc - TSTC)]$$

Where Gt is the irradiance on the panel (W/m²), A is the panel area (m²), ηSTC is the module efficiency at standard test conditions, γ is the temperature coefficient (%/°C), Tc is the cell temperature (°C), and TSTC is 25°C (standard test condition).

D. Wind Resource Assessment

Wind speed determination was performed using the power law to extrapolate wind speed data at various heights. The power law is expressed as:

$$V_2 = V_1 \times (Z_2/Z_1)^\alpha$$

Where V_2 and V_1 are wind speeds at heights Z_2 and Z_1 respectively, and α is the wind shear exponent (0.14 for open rural terrain). Monthly average wind speeds (Fig4) at the study location range from 3.04 m/s in December to 4.89 m/s in August at 100m hub height, with annual averages around 3.5-3.6 m/s.

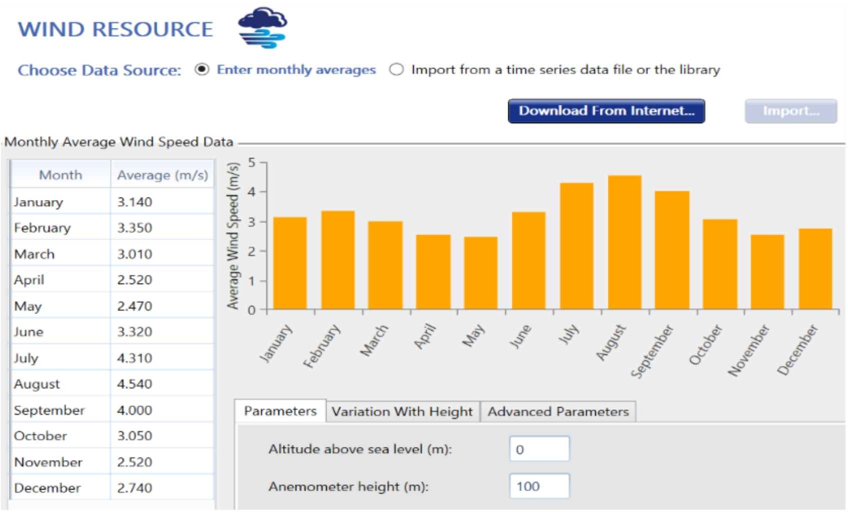

Fig4: Monthly average wind speed of Igwuruta, Rivers State (m/s) (src: Homer)

The Weibull parameters (shape parameter k and scale parameter c) were determined using the Power Density Method. The shape parameter k was evaluated as:

$$k = (\sigma / \bar{V})^{(-1.086)}$$

Using the empirical method of Justus, the Weibull scale parameter c is calculated as:

$$c = \bar{V} / \Gamma(1 + 1/k)$$

Where V̄ is the mean wind speed, σ is the standard deviation, and Γ is the gamma function. The analysis yielded a shape parameter k of 2.755 and scale parameter c of 6.05 m/s at 60m hub height.

The wind power density from the Weibull distribution parameters is estimated using:

$$WPD = 0.5 \times \rho \times c^3 \times \Gamma(1+3/k)$$

Substituting the values with ρ = 1.225 kg/m³, c = 6.05 m/s, and the appropriate gamma function values, the wind power density at 60m hub height was calculated to be approximately 135 W/m², classifying the region as a Class 2 wind resource (marginal for utility-scale but useful for hybrid configurations).

E. System Modeling and Simulation

Two primary software tools were employed for system modeling and simulation:

1) ETAP 19.0.1 for Electrical Analysis

The Electrical Transient Analyzer Program (ETAP) was used for load flow analysis and short circuit analysis of the SMCP distribution system. The single-line diagram was modeled with all system components including generators, transformers, and loads. The Load Flow Analysis (LFA) (Fig5) was performed using the Adaptive Newton-Raphson method, which provides a comprehensive and accurate understanding of the electrical power distribution system's steady-state behavior. The Short Circuit Analysis (SCA) (Fig6) was conducted per IEC 60909 standards to calculate fault currents and assess device duties.

The hybrid renewable energy system was modeled in ETAP with the following components: Grid interconnection at 33 kV (1000 MVAsc), 2x 7.5MVA step-down transformers (33/11kV), 2x 1MW wind turbines at 690V, 4x 1.225MVA PV arras at 600V, 2x 2.25MW diesel generators at 0.415kV, and 500kWh Li-ion battery storage.

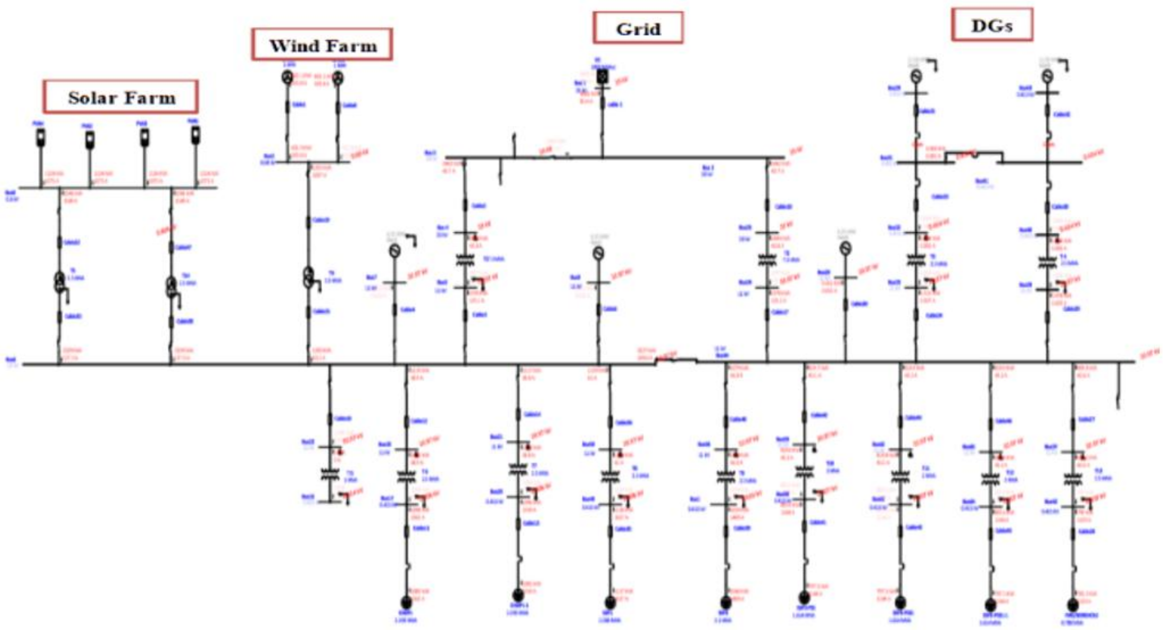

Fig5: LFA of study case, wind and solar Farm, Simulated using Electrical Transient Analyzer (ETAP 19.0.1)

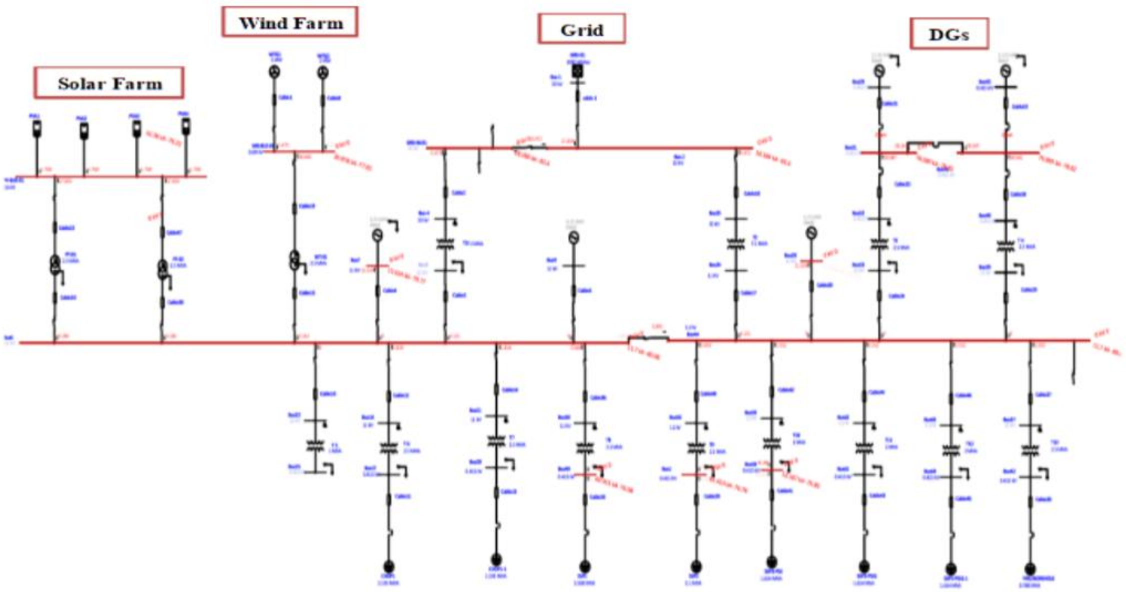

Fig6: SCA of Study case, wind and Solar farm, simulated using Electrical Transient Analyzer (ETAP 19.0.1)

2) HOMER Pro for Techno-Economic Optimization

The Hybrid Optimization Model for Electric Renewables (HOMER) was used for techno-economic optimization. The system configuration modeled in HOMER Pro included solar PV array (modular input with 5MW total capacity), wind turbines (2x 1MW units at 100m hub height), lithium-ion battery bank (500 kWh), small-capacity diesel generator (2x 2.25MW for backup), bidirectional inverter (5x 900kW with 90-95% efficiency), and local grid connection.

TABLE II: System Components and Specifications

Component	Size/Rating	Capital Cost (N)	Lifetime
Solar PV (Monocrystalline)	6626 x 750W	159,125/unit	25 years
Wind Turbine (LTW 80)	2 x 1 MW	520,800,000/unit	25 years
Battery (Li-ion)	5 x 100 kWh	1,280,000/unit	15 years
Diesel Generator (CAT-3516C)	2 x 2.25 MW	240,900,350/unit	80,000 hrs
Inverter (Leonics GTP519S)	5 x 900 kW	350,000,000/unit	20 years

F. Economic Analysis Methodology

The economic assessment employed multiple metrics including Net Present Value (NPV), Levelized Cost of Energy (LCOE), payback period, and Return on Investment (ROI). The NPV is calculated as:

$$NPV = \Sigma(Rt - Ct) / (1+r)^t$$

Where Rt is the revenue at time t, Ct is the cost at time t, and r is the discount rate. The LCOE is calculated as:

$$LCOE = (C_0 \times CRF + COM) / (Prated \times CF \times 8760)$$

Where CRF is the Capital Recovery Factor calculated as $CRF = r(1+r)^n / ((1+r)^n - 1)$, COM is the annual operation and maintenance cost, Prated is the rated power, and CF is the capacity factor.

The economic parameters applied in this study include: Discount rate of 25.4%, expected inflation rate of 15.2%, project lifetime of 25 years, diesel fuel cost of N1,200/litre, and grid electricity cost of N225/kWh based on NERC MYTO 2024.

V. RESULTS AND DISCUSSION

A. Load Flow Analysis Results

The ETAP-based analysis validated the technical feasibility of hybrid renewable energy integration in the existing 33/11 kV network in SMCP. The simulation was based on a simplified single-line diagram of the designed system architecture incorporating grid interconnection at 33 kV, 2x 7.5 MVA step-down transformer, distributed PV arrays, wind turbines, battery storage, and diesel backup units.

TABLE III: Summary of ETAP Simulation Results

Metric	Before Hybrid	After Hybrid	Improvement
Total Generation (MW)	6.455	22.7	+251%
Generation Mvar	4.421	4.713	+6.6%
Mismatch (MW)	0.0495	0.0211	57.4%
Voltage Deviation (Worst Bus)	-2.228%	-0.283%	87.3%
11kV Bus Voltage	10.966 kV	10.969 kV	Stable
Peak Fault Current @ 0.415kV	74.7 kA	76.1 kA	Within limits

The results show improved voltage profiles with voltage deviation reduced from -2.228% to -0.283%, representing an 87.3% improvement. The power mismatch was reduced by 57.4%, indicating better power balance after hybrid integration. The 11kV bus voltage remained stable at approximately 10.97 kV, confirming technical compatibility with the existing distribution infrastructure.

B. Wind Resource Analysis Results

The Weibull analysis yielded the following parameters at different hub heights:

TABLE IV: Weibull Parameters at Different Hub Heights

Parameter	40m	60m	80m	100m
Mean Wind Speed (m/s)	3.55	3.94	4.24	4.48
Shape Parameter (k)	2.755	2.755	2.755	2.755
Scale Parameter (c)	5.42	6.05	6.52	6.89
Wind Power Density (W/m²)	98.5	135.2	169.8	201.4
Capacity Factor (%)	5.2	7.06	8.9	10.5

The wind power density at 60m hub height was calculated to be approximately 135 W/m², classifying the region as a Class 2 wind resource. The capacity factor of wind turbines at this height was estimated at 7.06%, indicating that wind energy could serve as a complementary resource, especially during night-time or non-solar periods. The most probable wind speed (Vmp) and wind speed carrying maximum energy (VmE) were calculated as 5.28 m/s and 7.12 m/s respectively.

C. Solar Resource Analysis

The solar resource analysis confirmed strong potential for photovoltaic systems in the study area. The annual average daily solar irradiance of 4.53 kWh/m²/day, combined with the region's tropical climate, makes solar PV highly viable. The monthly variation shows peak irradiance during the dry season (January-April) with values exceeding 5.0 kWh/m²/day, while the wet season (June-September) shows reduced values of 3.0-3.5 kWh/m²/day. This seasonal complementarity with wind resources (which peak during the wet season) enhances the overall system reliability.

D. Techno-Economic Optimization Results

The HOMER Pro simulation identified the optimal hybrid configuration as PV-Wind-Battery-Diesel. The key economic metrics are presented in Table V:

TABLE V: Techno-Economic Summary of Optimal Hybrid System

Parameter	Value	Unit
Net Present Cost (NPC)	10.7	Billion Naira
Levelized Cost of Energy (LCOE)	54.60	N/kWh

Renewable Fraction	97.1	%
Annual O&M Cost	256	Million Naira
Initial Investment	8.18	Billion Naira
Simple Payback Period	2.25	Years
Discounted Payback Period	2.63	Years
Return on Investment (ROI)	39.1	%
Internal Rate of Return (IRR)	42.3	%

The optimal system configuration comprises 5 MW solar PV (6,626 panels of 750W each), 2 MW wind turbines (2 units of 1MW each), 500 kWh lithium-ion battery storage, and 4.5 MW diesel backup (2 units of 2.25MW each). The system achieves a renewable fraction of 97.1%, with diesel generators operating less than 10% of the time.

E. Cost Comparison Analysis

Table VI presents a comparative analysis of different system configurations:

TABLE VI: Cost Comparison of Different System Configurations

System Type	LCOE (N/kWh)	NPC (N)	Renewable Fraction	Annual Fuel Cost
PV+Wind+Battery+Diesel	54.60	10.7 billion	97.1%	Minimal
Diesel+Grid Only	486.00	37.8 billion	0%	5.59 billion
Grid Only	225.00	37.6 billion	0%	N/A
PV+Diesel	137.27	26.8 billion	52.4%	2.17 billion
Wind+Diesel	168.45	29.4 billion	38.7%	2.85 billion

The hybrid system demonstrates significant economic advantages, with an LCOE of N54.60/kWh compared to N486/kWh for diesel-only systems, representing an 88.8% cost reduction. Compared to grid-only supply at N225/kWh, the hybrid system offers a 75.7% cost saving. The NPC of N10.7 billion is 71.7% lower than the diesel-only alternative (N37.8 billion) and 71.5% lower than grid-only supply (N37.6 billion).

F. Energy Generation Profile

The energy generation profile from HOMER Pro simulation shows that solar PV contributes 94.9% of total energy production (22,537,725 kWh/year), wind turbines contribute 3.68% (618 MWh/year), and the diesel generator contributes only 1.42% during critical periods. The battery system provides load balancing and ensures continuous supply during non-solar hours. The system purchased only 580,895 kWh from the grid while exporting 2,935,811 kWh, resulting in a net energy export of 2,354,916 kWh and potential revenue of N130.6 million annually from energy sales.

G. Sensitivity Analysis

The sensitivity analysis evaluated the impact of key variables on system economics[14]:

1) Diesel Fuel Price Variation

The system showed minimal sensitivity to diesel price fluctuations over the range of N1,200 to N1,500 per litre, maintaining a constant LCOE of N54.60/kWh due to the high renewable fraction. This demonstrates the system's resilience to fossil fuel price volatility.

2) Load Demand Growth

A ±20% variation in load demand resulted in NPC ranging from N8.65 billion (20% decrease) to N12.8 billion (20% increase), with LCOE remaining relatively stable at N55-56/kWh. This indicates that the system maintains economic viability across a range of demand scenarios.

TABLE VII: Sensitivity Analysis Results

Variable	Range	NPC (N)	LCOE (N/kWh)
Diesel Price	N1,200/L	10.7 billion	54.60
Diesel Price	N1,500/L	10.7 billion	54.60

Load Demand	-20%	8.65 billion	56.03
Load Demand	Base Case	10.7 billion	54.60
Load Demand	+20%	12.8 billion	55.08
Discount Rate	18.4%	12.6 billion	33.90
Discount Rate	25.4%	10.7 billion	54.60
Discount Rate	27.2%	10.4 billion	61.33

3) Discount Rate Impact

The discount rate significantly impacts NPC, with rates of 18.4%, 25.4%, and 27.2% yielding NPC values of N12.6 billion, N10.7 billion, and N10.4 billion respectively. Higher discount rates reduce the present value of future costs, resulting in lower NPC but higher LCOE.

H. Environmental Impact Assessment

The proposed hybrid system contributes to substantial greenhouse gas emission reduction[5]. The annual carbon emissions comparison shows:

- Diesel-only system: 10,245 metric tons CO_2/year
- Grid-only system: 8,567 metric tons CO_2/year
- Hybrid system: 200 metric tons CO_2/year
- Net emission reduction: 10,045 metric tons CO_2/year (98% reduction)

This emission reduction supports Nigeria's climate commitments and global sustainability targets under SDG 13 (Climate Action). Additionally, by minimizing the use of diesel generators, the system helps mitigate air and noise pollution, improving public health outcomes[7] in the local community.

I. Resource Synergy and Complementarity

The combined solar and wind resource profile (Fig7) demonstrates complementary behavior that enhances system reliability. Solar PV dominates during the day and dry season (January-April), while wind energy becomes more relevant in early mornings, evenings, and during the wet season (June-September) when solar irradiance is reduced. This temporal complementation justifies the inclusion of wind turbines in the hybrid model, even though their contribution remains secondary to solar. The battery storage system bridges the gap during periods of low renewable generation, ensuring 24/7 power supply reliability.

Fig7: Share of Energy Supplied from Each Energy Source (src: Homer)

VI. CONCLUSION

This research has evaluated the feasibility and impact of integrating hybrid renewable energy systems into the Salvation Ministries Cathedral Project in Igwuruta, Rivers State, Nigeria. The study addressed the critical energy challenges faced by large institutional facilities in Nigeria, where unreliable electricity supply from the national grid disrupts operations and escalates operational costs through heavy reliance on diesel generators.

The key findings of this research are summarized as follows:

- The PV-Wind-Battery-Diesel hybrid configuration achieved a Levelized Cost of Energy (LCOE) of N54.60/kWh, which is significantly lower than the N486/kWh for diesel-only generation and N225/kWh for grid-only supply, representing cost reductions of 88.8% and 75.7% respectively.
- The optimal system configuration comprises 5 MW solar PV, 2 MW wind turbines, 500 kWh battery storage, and 4.5 MW diesel backup, achieving a renewable fraction of 97.1% with diesel generators operating less than 10% of the time.
- The system demonstrates a favorable payback period of 2.25 years (simple) or 2.63 years (discounted) and a return on investment of 39.1%, establishing strong financial viability under current market conditions.
- ETAP simulation results confirmed technical compatibility with the existing 33/11 kV distribution network, with improved voltage profiles (87.3% reduction in voltage deviation) and reduced power mismatch (57.4% improvement) after hybrid integration.
- The system reduces CO2 emissions by over 10,045 metric tons annually (98% reduction), contributing significantly to environmental sustainability goals and supporting Nigeria's commitments under the Paris Agreement and SDG 13.
- Sensitivity analysis confirmed the system's economic resilience across a range of fuel prices, load demand scenarios, and discount rates, making it a robust investment for institutional energy infrastructure.

The findings affirm the strategic role of decentralized hybrid microgrids in advancing rural electrification and provide actionable insights for policymakers, investors, and regulators navigating sub-Saharan Africa's dynamic energy transition. The methodology and results presented in this study can be replicated for similar large institutional facilities across Nigeria and other developing nations facing similar energy challenges.

VII. RECOMMENDATIONS

A. Deployment-Level Recommendations

Based on the technical and economic findings of this study, the following deployment-level recommendations are proposed:

- Solar PV, supported by battery storage and backed by diesel generation, should be prioritized as the core hybrid model due to its strong performance in terms of availability, cost-effectiveness, and scalability[4]. The high solar irradiance in Rivers State (4.53 kWh/m²/day) makes solar PV the primary energy source.
- Wind energy may be included where localized data supports moderate wind speed (>3 m/s at 60m hub height) to complement solar intermittency, especially during the rainy season. The Class 2 wind resource at the study site (135 W/m² at 60m) provides marginal but useful supplementary generation.
- Load assessments should be conducted at the facility level using smart meters, field surveys, and seasonal usage patterns to ensure that system design accurately reflects real demand and prevents under- or over-sizing.
- Battery storage is a critical component of system reliability. Provisions for battery replacement every 10-15 years (for Li-ion) should be built into thefinancial planning. Establish battery recycling partnerships to prevent environmental hazards associated with battery disposal.
- Engage local technicians and electricians through training and apprenticeship programs to support the installation, maintenance, and troubleshooting of hybrid systems. Involve community members in system monitoring to foster a sense of ownership and long-term sustainability.

B. Policy and Institutional Recommendations

The following policy recommendations are proposed to support the widespread adoption of hybrid renewable energy systems:

- The government should introduce fiscal incentives such as import duty waivers, value-added tax (VAT) exemptions, and capital subsidies for renewable components, especially solar panels, batteries, and inverters. These incentives can reduce the initial capital cost barrier by 15-25%.
- Consider implementing feed-in tariffs or net metering policies for hybrid mini-grids with excess generation capacity. The study demonstrated net energy export potential of 2.35 GWh/year, which could generate N130.6 million in annual revenue.
- Develop low-interest loan schemes and concessional financing windows through the Rural Electrification Agency (REA), Bank of Industry (BoI), or green finance mechanisms for mini-grid developers and energy cooperatives.

- Support result-based financing and public-private partnerships to scale deployment and reduce upfront cost barriers. The favorable ROI of 39.1% makes these projects attractive for private investment with appropriate risk-sharing mechanisms.
- Encourage the use of software tools like HOMER Pro and ETAP in energy planning by utilities, regulators, and project developers to ensure accurate techno-economic assessment and optimal system design.
- Strengthen the role of government agencies and electricity distribution companies in supporting mini-grid development through land provision, security assurance, and community mobilization.
- Simplify licensing and interconnection processes for grid-tied hybrid systems to attract more private sector participation and accelerate deployment.

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