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Techno-Economic Analysis of Renewable Distributed Generation Integration into Rural Distribution Network for Improved Power Supply

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Abstract- The ultimate goal of this paper is to assess the techno-economics of integrating renewable distributed generation (RDG) to the Yahe – Ogoja rural distribution network, Cross River, Nigeria. The integration of hybrid solar photovoltaic (PV) and wind energy system with existing grid network using MATLAB / Simulink for technical simulation and HOMER Pro for economic optimization is considered in the study. Findings of network assessment indicated there is voltage instability and high losses of real power. After optimization with the PSO and MCDA techniques, Bus 20 was determined to be the ideal site for the placement of distributed generation. The Other Performance Tool was used for this purpose. It was determined that an installation power of 1315 kW and renewable penetration level of 72% are optimum at bus 20. The solar PV power output which was recorded varied from 175.5 kW to 338.5 kW, with an average of 255 kW and the wind power output varied from 4 kW to 306 kW depending on wind speed conditions. The technical findings demonstrated enhanced voltage stability, diminished real power losses, and THD values under the limit of 3% standard acceptable. Economic analysis showed that the NPC was financially attractive when considering a project life of 25 years, while LCOE was reduced from $0.06/kWh to $0.045/kWh, a reduction of 25%. The system achieved a payback period of 7.5 years and a Benefit-Cost Ratio (BCR) of 1.4. In addition, cumulative carbon emission savings reached 1,250 tons of CO_2 ***over the project lifespan. The study concludes that optimized hybrid renewable distributed generation offers a technically reliable, economically viable, and environmentally sustainable solution for enhancing electricity supply in rural communities.***

Keywords: Renewable distributed generation; Rural distribution network; Total harmonic distortion; Wind energy; Techno-economic analysis; HOMER Pro; Particle Swarm Optimization.

I. INTRODUCTION

Electrical energy is the main form of energy which mankind uses to enhance socio-economic development, technological advancement and industrialization of their countries (Burke et al., 2018). Adequate access to electric energy is the lifeline of modern economies, it plays a critical role in poverty alleviation, reduction in infant mortality, long life expectancy and rapid urbanization in developing countries (Ritchie et al., 2019). Therefore, in the 21st century the need for electrical energy can never be over emphasized, since it is the key to the fulfillment of basic individual and communal need in the society today (Hassan & Hussain, 2019).

However, many rural communities in Nigeria, such as Yahe-Ogoja, load demand is growing unabated due to increase in population and increase in small scale bussiness.in the area, coupled with increase in prices of fossil fuel, as well as emissions of greenhouse gas during combustion of fossil fuel while generating electricity through independent diesel generators Conventional grid expansion to sparsely populated rural areas is usually expensive because of the high cost of transmission line extension, transformer installation, and continuous maintenance. These limitations often result in low voltage at remote buses, excessive technical losses, unstable power quality, and long outage durations (Adua et al., 2025). As a result, voltage instability, frequent outages, and poor power quality remain persistent problems that hinder socio-economic development and quality of life in rural communities (Akinwale et al., 2021).

As a result, focus has shifted to decentralized energy solutions like Renewable Distributed Generation

(RDG) as a sustainable solution to improve performance of distribution network (Kumar & Singh, 2020). Technologies such as solar photovoltaic (PV) and wind energy systems are renewable distributed generation (RDG) technologies that can provide rural electrification benefits (e.g. Nearness to the loads, lesser current flow through the feeder, betterment of supply voltage profile, and reduced real and reactive power losses).

Nigeria enjoys ample solar irradiation and moderate wind resources, especially in its rural areas. Because of this, hybrid solar–wind systems with battery storage are technically attractive for distributed applications (Olatomiwa et al., 2022). These systems mitigate reliance on extensive transmission lines as they produce power in proximity to the consumption point, leading to increased supply reliability and enhanced overall network efficiency, once sized and positioned appropriately (Manditereza & Bansal, 2016)

According to a report issued by Amewornu (2021), it was found that the grid-connected distributed renewable systems improve technical performance in terms of reliability indices. Also, it reduces the active power losses as well as the long-term operating cost. Further report by Enyewa et al. (2023) also finds the same result as above. All that said, it is necessary to conduct technical analyses such as voltage profile assessment, loss reduction evaluation, harmonic distortion analysis, etc., before and after the integration of RDG for safe and reliable operation.

Besides technical performance, renewable DG deployment should also be analyzed from the economic perspective. It means analyzing the Net Present Cost (NPC), Cost of Energy (COE) and operating cost to determine long-term viability. This is especially beneficial for rural communities with limited purchasing power.

According to Ekren & Ekren (2022), the techno-economic optimisation of hybrid renewable systems was conducted, but their work did not include detailed distributions network constraints like harmonic distortion, among others. Likewise, the work of Ukoima et al. (2023) studied the integration of renewables in distribution networks but mainly focused on simulation-based models without sufficient validation using real rural network data.

Therefore, this study fill the identified gaps through a detailed assessment of technical and economic impacts of integrating RDG (solar PV and wind energy) into Yahe–Ogoja rural distribution network in Cross River State, Nigeria, with the expectation of improving power supply. The specific objectives are to: (i) Assess baseline performance of the rural distribution network and evaluate the impact of penetrating RDG(solar photovoltaic (PV) and wind energy) on parameters such as: voltage instability, power losses, harmonic distortion, (ii) determine the optimal size of RDG units and harmonic mitigation devices considering network constraints for overall system improvement, and (iii) analyze and interpret the technical, economic, and power quality impacts of RDG integration, in compliance with standard benchmark using a techno-economic and multi-criteria decision approach.

II. MATERIALS AND METHOD

The materials and tools used for this research work are: Distribution network data, renewable energy resource data and software tools. Distribution network data consists of One Line Diagram (SLD) of the network, load and bus data, as well as transformer ratings and connection types. Renewable energy resources data comprises of solar irradiance data (kWh/m²/day), wind speed data (m/s) at reference height and meteorological data (climate records) obtained from NASA databases and regional climate records.

MATLAB/Simulink tool was employed for load flow analysis, harmonic analysis, and implementation of PSO for optimal RDG sizing and placement, while, HOMER Pro software was employed for techno-economic analysis.

The method used in this research is based on analysis and simulation using MATLAB (11kV Network) and Homer (33kV Network). The distribution network is modeled under two operating conditions namely; Base Case: Existing network without RDG integration, and Optimized Case: Existing network with RDG (Solar PV and Wind energy) integration.

To achieve the objectives of this study, the following methods are adopted: Techno-Economic analysis and Multi-Criteria Decision Average (MCDA). The Particle Swarm Optimization (PSO) method was used to analyze the 33kV network.

Study Area Description

The Yahe-Ogoja community, Cross Rivers State, Nigeria lies between latitude 6°39.2' N and longitude 8°48.0' E. The study area geographical definition allows HOMER Pro to reference weather and renewable energy databases suitable for the region, including solar irradiance, temperature trends, and wind speed conditions. The system automatically selects UTC +01:00, matching the West Central Africa time zone. The major occupation of the inhabitants of community is farming, fishing, trading, small and medium-scale enterprise like barbing, auto mechanics etc.

The community average daily load demand is 109,432.01 kWh/day with a peak of 6,393 kW represents the energy consumption level of the 33 kV distribution feeder supplying the Yahe–Ogoja.

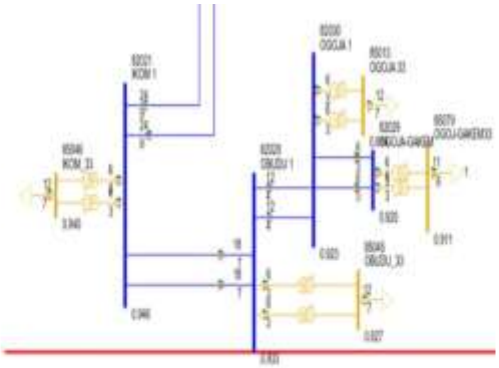

Figure 1: One Line Diagram of the Considered Section of Yahe-Ogoja Network. Source: Port Harcourt Electricity Distribution Company (2025)

Table 1: Distribution System Information

Parameter	Value
Network Type	Radial
Number of Load buses	4
Transformer Per Load Bus	2
Transformer Rating (Load Bus)	200kVA,300kVA,500kVA
Power Transformer Rating	15MVA
Line Type	Overhead
System Voltage (Primary)	33kV
System Voltage(secondary)	11kV
Source	33kV Utility Grid

Source: Port Harcourt Electricity Distribution Company (2025)

Table 2: Bus and Load Data (Power Factor at 0.85)

Bus id	Bus No	Bus Name	Description	Volts p.u.	P(MW)	Q(MVAR)
1	82021	Ikom 1	Slack (PV)	0.946	15.00	00.00
2	82030	Ogoja 1	PV	0.923	15.00	00.00
3	85079	Ogoja-Gakem 33	PQ	0.911	11.43	6.32
4	85045	Obudu 33	PQ	0.927	12.31	6.64

Source: Port Harcourt Electricity Distribution Company (2025)

Table 3: Line Data between Buses (Overhead)

From	To	R (p.u.)	X (p.u.)	B (p.u.)
4	1	0.0162	0.0517	0.0471
4	2	0.0159	0.0506	0.0460
3	2	0.0106	0.0337	0.0307

Source: Port Harcourt Electricity Distribution Company (2025)

Table 4: Monthly Average Global Horizontal Irradiance (GHI) for YAHE–Ogoja

Month	Clearness Index	Daily Radiation ($kWh/m^2/day$)
January	0.620	5.770
February	0.594	5.860
March	0.546	5.610
April	0.511	5.340
May	0.495	5.060
June	0.467	4.690
July	0.447	4.460
August	0.395	4.090
September	0.425	4.390
October	0.472	4.860
November	0.555	5.220
December	0.611	5.510

Source: NASA Database (2025)

Table 5: Monthly Mean Wind Speed Data (m/s) for YAHE–Ogoja

Month	Average Wind Speed (m/s)
January	2.790
February	2.870
March	2.820
April	2.610
May	2.480
June	2.460
July	2.760
August	2.880
September	2.670
October	2.810
November	2.500
December	2.460

Table 6: Input Data and Parameters for MATLAB/ HOMER Pro SIMULATION

Category	Field	Unit	Description	Value
Project Information	Location	-	Study area	Yahe-Ogoja, Ogoja LGA, Cross River State, Nigeria
Project Information	Latitude	Decimal degrees	Site latitude	6°39′3″ N
Project Information	Longitude	Decimal degrees	Site longitude	8°47′4″ E
Project Information	Elevation	M	Site elevation above sea level	85
Project Information	Time Zone	UTC	Local time zone	+01:00
Project Information	Currency	-	Economic analysis currency	NGN (Naira)
Project Information	Project Lifetime	Years	System lifetime	25
Project Information	Analysis Start Year	Year	Simulation base year	2025
Electricity Load	Daily Energy Consumption	kWh/day	Average daily load demand	10,342.01
Electricity Load	Peak Demand	kW	Maximum instantaneous load	6,339
Solar Resource	Solar Data Source	-	Source of solar data	NASA
Solar Resource	PV Azimuth	Degrees	Orientation (South-facing)	180

Wind Resource	Cut-in Speed	m/s	Minimum operational speed	2.5
Wind Resource	Rated Speed	m/s	Rated turbine speed	12
Wind Resource	Cut-out Speed	m/s	Maximum allowable speed	30
Battery Storage	Battery Model	-	Battery chemistry	12 V Lead-acid
Battery Storage	Rated Capacity	Ah	Nominal capacity	83.4
Battery Storage	Depth of Discharge	%	Maximum DOD	40
Power Electronics	Converter Efficiency	%	Conversion efficiency	95
Economic Parameters	Discount Rate	%	Real discount rate	8
Economic Parameters	Inflation Rate	%	Annual inflation	2
Economic Parameters	Exchange Rate	NGN/USD	Currency conversion	1,500

Source: NASA (2025) & Authors

Design and Modeling of Solar PV System

HOMER Pro Software is used to optimize for the needed capacity to be used. It is assumed that the solar PV modules have a maximum power plant tracking (MPPT) system with associated parameters and values such as capital cost of $3500/kW, replacement cost of $3500/kW, operation/maintenance cost of $50/year, efficiency of 17%, operating temperature of47°C, temperature coefficient of – 0.5, derating factor of 85% and life span of 25 years.

HOMER Pro Software calculate the output of the PV array for each time step using the equation:

$$P_{PV} = Y_{PV} F_{PV} \left(\frac{G_T}{G_T STC}\right)[1 + \propto_P (T_C - T_C STC)] \qquad (1)$$

Where;

Y_{PV} = the rated capacity of the PV array (kW)

F_{PV} = the PV derating factor (%)

$G_T =$ the solar radiation incident on the PV array (kW/m^2)

$G_T ST_C =$ the incident radiation at standard test condition (1kW/m^2)

$\propto_P$ = the temperature coefficient of power (%/°C)

T_C = the PV cell temperature (°C)

$T_C ST_C$ = the PV cell temperature under standard test conditions (25°C)

Design and Modelling of Wind Energy System

The instantaneous power output of the wind turbine generator can be expressed as:

$$P_{WT} = C_s C P \rho \pi R^2 V^3 \qquad (2)$$

Parameter;

P_WT = the power derived from a wind turbine (in watts)

C_S= the aerodynamic power coefficient = 0.593

C_P= the coefficient of performance (efficiency factor in percentage).

ρ = the air density (in kg/m3)

R= the blade length (in meters)

V= the wind speed (in meters per seconds).

The chosen wind turbine model has cut in speed of 2.5m/s, rated speed of 12m/s, cut out speed of 30m/s, swept area of 500m2, height hub of 40m, with installation cost of $30,000/unit and a life span of 25 years.

Battery Model Selection

A generic 12V, lead acid solar battery was selected in this design. The rated capacity 83.4Ah, 80% charge efficiency. 40% depth of discharge, maximum charging current of 16.7A, installation cost of $500/kW, operational/maintenance cost of $30/year and lifetime of 10years, maximum discharge current of 24.3A. The autonomy of the battery can be determined using:

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left[\frac{1-q_{min}}{100}\right] \left({}^{24h}/_{d}\right)}{L_{prim.ave}(100Wh/kWh\,)} \tag{3}$$

Where;
A_batt= the storage battery bank autonomy (hrs)
N_batt= the number of batteries in the storage bank.
V_nom= the nominal voltage of a single storage (V)
Q_nom= the nominal capacity of a single (Ah)
q_min= the minimum state of charge of the storage bank (%).
L_(prim.ave)= the average primary load (kWh/d)

Converter Model

The inverters convert DC power to AC power whenever there is a need for AC power in the distribution grid power system with DGs. The associated relationship is

E_inv (t)=(E_(Bat) (t)+E_pv (t)) ×η_inv (4)

Were,
E_inv (t) = the energy output of the inverter in kWh.
E_(Bat) (t) and E_pv (t) = energy stored in battery bank and energy generated by PV array.

Generic converter power model with a capital cost of \$300/kW, replacement cost of \$300kW, operation/maintenance cost of \$0, a lifetime of 15years and an inverter efficiency of 95% was selected.

Annual System Energy Production

Total annual energy productions involve the hybrid of renewable energy (solar PV and wind energy) and grid system energy. Therefore, annual electricity production is expressed as:

Eannual = EPV +EWT +Egrid (5)

Where:
EPV = Annual energy from Solar PV (kWh/year)
EWT = Annual energy from wind turbine (kWh/year)
Egrid = Annual energy imported from the grid (kWh/year)

Load Flow Analysis Using Newton-Raphson

Newton–Raphson (NR) iterative technique was ad for load flow analysis. For a system with n buses, the real and reactive power injected at bus i are expressed as

$$P_i = \sum_{k=1}^{n} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \cos(\delta_k + \theta_{ik} - \delta_i) \tag{6}$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_{\mathrm{i}}||V_{\mathrm{k}}| \sin(\delta_k + \theta_{ik} - \delta_i) \tag{7}$$

Where;
Y_ik= admittance
P_i= real power
Q_i= reactive power
δ_i= phase angle

The mismatch equations at each iteration k are given by

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \left|\begin{matrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \\ \left|\begin{matrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{matrix}\right| & \left|\begin{matrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{matrix}\right| \end{bmatrix} \begin{bmatrix} \Delta\delta_2^{(k)} \\ \vdots \\ \Delta\delta_n^{(k)} \\ \hline \Delta\left|V_2^{(k)}\right| \\ \vdots \\ \Delta\left|V_n^{(k)}\right| \end{bmatrix} \tag{8}$$

With minor changes in real ΔP_i^((k)) and reactive power ΔQ_i^((k))the Jacobian matrix shows the linearized correlation between tiny changes in voltage angle Δδ_i^((k)) and magnitude Δ|V_i^((k)) |

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \tag{9}$$

Where;
J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

The voltage corrections are obtained by solving the linearized Jacobian system

$$[\Delta P\ \Delta Q]^{\mathrm{T}} = J\,[\Delta\theta\ \Delta|V|]^{\mathrm{T}} \tag{10}$$

Where J is the Jacobian matrix containing the partial derivatives of the power equations with respect to voltage angles and magnitudes.

Optimal Distributed Generation Size

The optimization of the proposed DG system is based on the PSO, which follows the load flow considering Voltage Deviation Index, Active Loss Index and Voltage Stability Index specifically constrained in an adaptive manner by active shunt compensating devices for loss minimization and harmonic filtering. This equation supports techno-economic optimization.

$$P\_DG = P\_load \times \alpha \quad (11)$$

Where:
P_DG= Distributed generation size
P_load= Load demand
α= Penetration factor

Voltage Stability Index (VSI)

Voltage Stability Index evaluates the ability of a bus to maintain voltage under load changes. It supports DG placement for voltage enhancement. This metric ensures network reliability.

$$VSI = \frac{4R}{(P+Q)^2} \quad (12)$$

Where:
VSI=Voltage stability index
R= Resistance
P, Q= Real and reactive power

Real Power Loss

Real power loss quantifies energy dissipated in distribution lines due to resistance. It reflects network inefficiency and impacts operational costs. This equation is fundamental for evaluating technical losses before and after distributed generation integration.

$$P_{loss} = \sum_{k=1}^{L} I_k^2 R_k \quad (13)$$

Where:
P_loss= Real power loss
L= Number of lines
I_k= Current in line k
R_k= Resistance of line k

Total Harmonic Distortion (THD)

Total Harmonic Distortion measures the distortion in voltage or current waveforms caused by nonlinear loads. This metric evaluates harmonic effects before and after mitigation.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% \quad (14)$$

Where:
THD= Total Harmonic Distortion
V_n= Voltage of nth harmonic
V_1= Fundamental voltage

Multi-Criteria Decision Score (MCDA)

MCDA aggregates multiple criteria for optimal decision-making. It evaluates technical and economic factors to rank DG placement options. This method supports structured and data-driven decisions.

$$MCDA = \sum_{i=1}^{n} w_i \times C_i \quad (15)$$

Where:
MCDA= Decision score
w_i= Weight of criterion
C_i= Criterion value

Net Present Cost (NPC)

Net Present Cost assess the total lifecycle cost of the system. This metric supports techno-economic decision-making.

$$NPC = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (16)$$

Where:
NPC= Net present cost
C_t= Cost at time t
r= Discount rate

Levelized Cost of Energy (LCOE)

Levelized Cost of Energy measures the unit cost of electricity generation. This metric is critical for financial feasibility analysis.

$$COE = \frac{NPC}{E_{total}} \tag{17}$$

Where:
COE= Cost of energy
E_total= Total energy generated

Benefit-Cost Ratio (BCR)
Benefit-Cost Ratio compares system benefits to implementation costs. This metric evaluates project feasibility.

$$BCR = \frac{Benefits}{Costs} \tag{18}$$

Where:
BCR= Benefit-cost ratio
Payback Period (PP)
Payback period measures the time required to recover investment costs. It supports economic feasibility assessment. This metric evaluates investment risk.

$$PP = \frac{Initial\ Investment}{Annual\ Savings} \tag{19}$$

Where:
PP= Payback period
Overall System Performance (OSP)
Overall system performance aggregates technical and economic metrics. It supports holistic evaluation of DG integration. This metric validates system effectiveness.

$$OSP = \sum_{i=1}^{n} w_i \times M_i \tag{20}$$

Parameters:
OSP= Overall performance
M_i= Performance metric
w_i= Weight of metric

III. RESULTS AND DISCUSSION

Output Power of Solar Photovoltaic (PV) and Wind Energy System
Figures 2 and 3 illustrate the calculated output power of the solar PV and wind energy systems, respectively. As shown in Figure 2, the solar PV output ranges from 175.5 kW to a peak of 338.5 kW during periods of high solar irradiance. The close linear relationship with irradiance confirms that the adopted 50-scale conversion is effective. The average output of 255 kW is also a significant parameter for proper sizing of distributed generation units.

According to Figure 3, wind power output can be modeled by cubic relationship with wind speed, resulting in major variations. The high point of the output is around 306 kW while the low point is as low as 4 kW. It indicates that wind energy contributes only when the situation is beneficial however, one system PV system is the main base-load source.

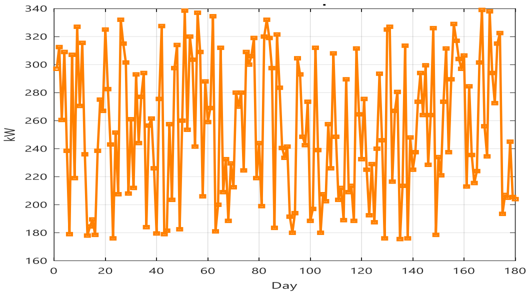

Figure 2: Plot of Solar PV Power Output

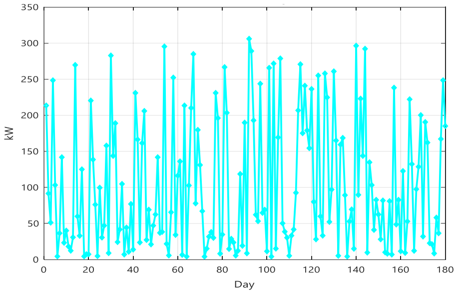

Figure 3: Plot of Wind Power Output

Voltage Stability Index
Network Voltage Stability Index (VSI) is illustrated in figure 4. The results obtained from study indicate a value of 0.02 to 0.08 for all 27 buses. When the index value is higher, it means the bus is closer to the voltage collapse point. The graph reveals key nodes

likely to become unstable under peak loading conditions. The purpose of this study is to ensure that the grid will remain stable during a sudden change in load.

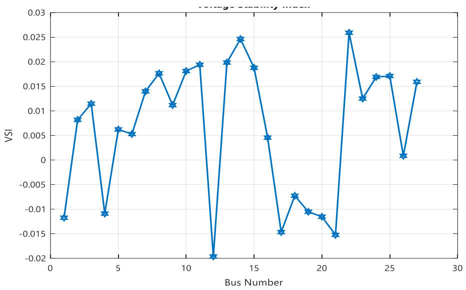

Figure 4: Voltage Stability Index (VSI) Versus Load Bus

Optimal Distribution Generation Sizing

The Loss Sensitivity Factor (LSF) and Voltage Stability Index (VSI) for crucial buses are presented in Figure 5 for 27-bus distribution system along with the parameters for renewable energy integration and Optimization. The analysis indicates that the value of LSF Bus 20 (approx 0.26) can be considered the best location for DG installation having 1315 kW capacity. Additional results demonstrate a renewable DG penetration level of 72%, while the grid provides the other 28%, indicating significant movement toward system autonomy.

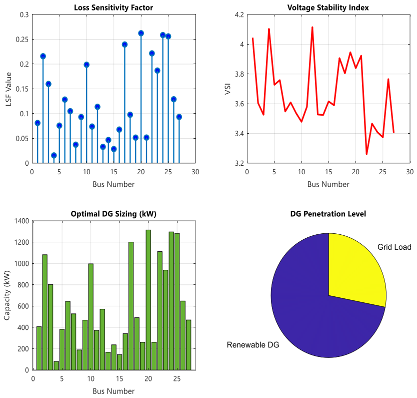

Figure 5: DG Sizing and Placement

Real Power Loss

Figure 6 shows the active power loss appearing across the buses in the network. Bus 25 has the highest loss value equal to approximately 2585 kW making it the most loaded bus. The findings indicate that the loss distribution is non-linear since only a few vital buses are responsible for most of the loss in the system. Lowering these losses can improve financial performance, increase system efficiency, and reduce transformer loading.

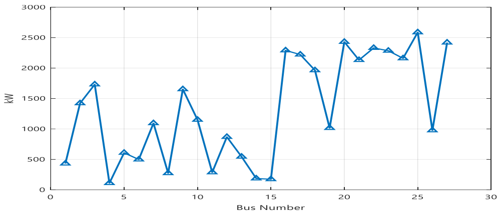

Figure 6: Real Power Loss Versus Load Bus

Total Harmonic Distortion

The total harmonic distortion levels in the buses is shown by fig.7. THD values were found to be a maximum of 0.03 which was well below the allowable limit of 3%. Harmonic filtering for the Power electronics and inverter systems are adequate for good power quality. When THD levels are lower the lifespan of consumer equipment is increased and it shows the technical compatibility of the renewable units proposed with 11 kV distribution system at Yahe-Ogoja.

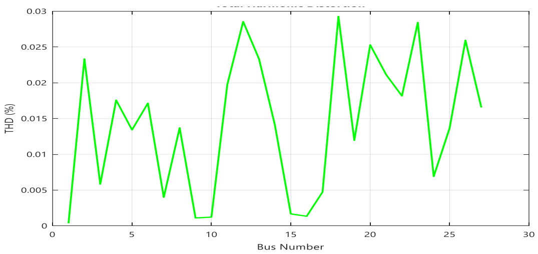

Figure 7: Total Harmonic Distortion Versus Load Bus

Multi-Criteria Decision Analysis (MCDA) Suitability Score

The multi-criteria decision analysis (MCDA) suitability score shown in Figure 8 for DG placement varies between 0.1 and 0.9 based on technical, economic and environmental conditions. Buses with a score of over 0.7 are considered highly suitable for PV or wind installation. The results indicate that not necessarily the technically best bus is the most economical, with the varying levels of suitability. The combination of a technical efficiency and environmentally, supports a balanced placement strategy.

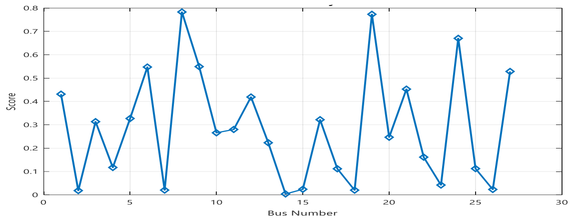

Figure 8: MCDA Suitability Score Versus Load Bus

Net Present Cost

The NPC value of the project during 25 years lifecycle is shown in Figure 9. It is found that the first cost is $600,000 but it declines in present-value terms because of the 8% discount rate factor applied. The study shows that with high first capital investment, the project will become economically viable due to reduced fuel use and energy purchases from grid in the long run.

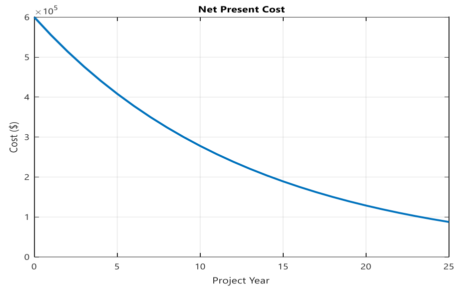

Figure 9: Net Present Cost Versus Project Year

Levelized Cost of Energy

As seen in Figure 10, the Levelized Cost of Energy (LCOE) decreases from a value of $0.06/kWh for the base design to $0.045/kWh for the optimized hybrid design. The reduction in electricity expenses is 25%, which makes the system at par with grid tariff. The optimization improves the technical performance and economic feasibility of the Yahe–Ogoja hybrid system.

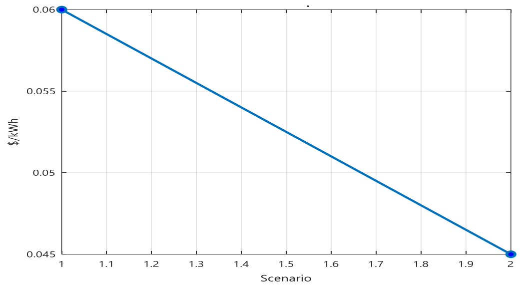

Figure 10: Plot of Levelized Cost per kWh

Carbon Emission Savings

The carbon emissions saved during the life of the project is presented in figure 11. The findings indicate that one thousand two hundred fifty tons of CO_2 were saved at the end of the 25th year. The steady linear trend shows a continuous displacement of fossil-fuel-based grid electricity by clean renewable energy which has a strong environmental rationale for the project.

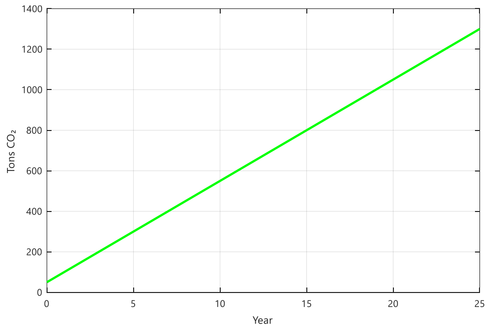

Figure 11: Carbon Emission Versus Year

Payback Period

The payback progress of an initial investment, in Figure 12. As per the results, the cost is $1.5 million, while the break-even point is around seven and half years. Such strong financial returns for a 25-year project indicate that the system's costs will be recovered well before the end of its life.

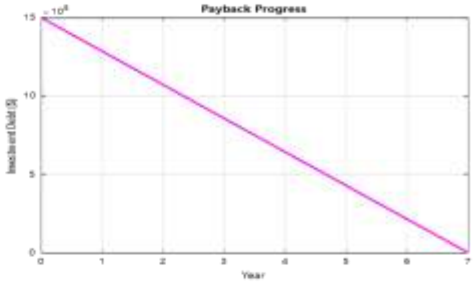

Figure 12: Payback Progress Versus Year

Benefit-Cost Ratio

As depicted in Figure 13, the project's Benefit-Cost Ratio (BCR) rises from 1.1 to 1.4 after the optimization. A Benefit to Cost ratio or BCR above 1.0 means that benefits exceed costs. Thus, the results show that $1.00 investment yields $1.40 in energy savings, loss reduction and better reliability. The optimized hybrid system confirmed as a worthwhile investment for the Ogoja area.

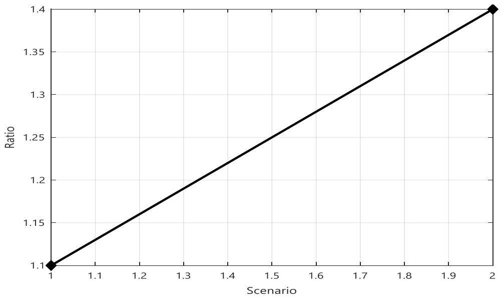

Figure 13: Plot of Benefit Cost Ratio

Overall System Performance

The Overall System Performance (OSP) score of the system increased from 0.60 to 0.85 after optimization. The index consists of technological, economic, environmental and reliability factors. The notable enhancement affirms that the enhanced hybrid renewable system is capable of providing a good and near-optimal solution to the Yahe–Ogoja distribution network.

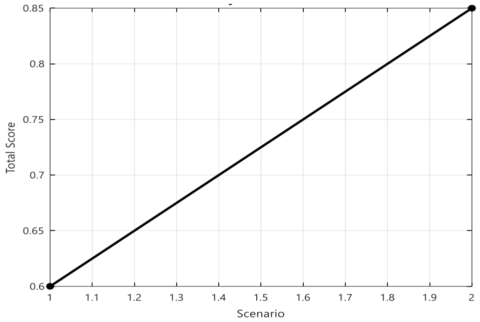

Figure 14: Plot of Overall System Performance

CONCLUSION

The outcomes of this assessment would be beneficial in the technical and economic viability of the integration of renewable distributed generation in the Yahe–Ogoja rural distribution network for power supply improvement. The existing system suffers from voltage instability, technical losses and excessive reliance on grid electricity. The network performance and reliability of supply considerably improved through the integration of hybrid solar PV and wind energy.

Based on the optimization result, the bus location which is bus 4 was found to be the most optimal. After this, the optimal DG capacity is 1315 kW. The renewable penetration comes out to be 72%, while grid dependence reduces to 28%. Technical analysis showed improvement in voltage profile, enhanced voltage stability, lesser real power losses, and THD (Total Harmonic Distortion) values found to be within 3 % which is the acceptable limit of the existing system.

According to economic assessment, project closely feasible with Levelized Cost of Energy at $0.045/kWh, payback period of 7.5 years and Benefit-Cost Ratio of 1.4. The project lifetime, the system delivered a total of savings of 1,250 tons of CO_2 in carbon emissions.

The optimal design of hybrid renewable distributed generation can provide reliable, cost-effective and environmentally-friendly rural electrification according to the research.

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