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ORIGINAL RESEARCH ARTICLE

OPTIMIZATION OF THE INDUSTRIAL USE OF RENEWABLE ENERGY FOR SUSTAINABLE AND COST-EFFECTIVE RURAL ELECTRIFICATION

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ABSTRACT

There is an inequitable access of rural communities to electricity services in Nigeria as demand supersedes generation. The provision of viable electricity to rural communities is hampered by some inefficiency bedeviling the allocation of energy resources coupled with the near depletion of fossil fuels. Due to capital intensive nature of renewable energy sources; most of these energy sources remain unexploited in Nigeria. This study aims at developing a general framework that can be utilized in Nigeria to minimize the total cost of installing renewable energy technologies while satisfying some predetermined constraints such as demand, supply and renewable energy potentials. Three scenarios were presented namely; prospective off-grid which accesses electricity level below 50%, on-grid which accesses electricity level above 50% and all-off-grid which finds the optimal cost of installing off-grid renewable energies. The results show that the total installation costs of the first and second scenarios are ₦42,656,292,800 and ₦49,908,650,400 respectively while that of the third scenario is found to be ₦106,938,354,400 which represent the extent of renewable energy resources that could possibly incentivize the realization of wider renewable energy applications in rural Nigeria. Furthermore, it was observed that the combination of the off-grid and on-grid installations have the potential for a decentralized renewable energy resources, with minimum installation cost. This will not only improve the wellbeing of rural communities, but also enhance Nigeria's energy and economic prospects for potential global investments.

1.0 Introduction

The importance of electricity on the socio-economic transformation of rural development cannot be over emphasized. According to the International Renewable Energy Agency (IRENA, 2019), item Seven (7) of the United Nations (UN) 2030 millennium Sustainable Development Goals (SDGs) focuses on affordable and clean energy. Currently, Nigeria's sources of electricity are far from being affordable and accessible. Despite the importance of electricity to the economy and rural dwellers who are mainly agrarian that need electricity to preserve their agricultural produce, they are still being constrained by lack of adequate and reliable electricity (Ajayi, 2009). Nigeria is endowed with abundant renewable energy (RE) that can be exploited for rural electrification at a considerable and affordable cost. The Nigerian nation is endowed with various RE mix such as: wind, solar, biomass and hydropower (Akorede *et al*., 2017). The big hydropower (BHP) sources are the major contributors of electricity in Nigeria accounting for almost 10,000 MW of electricity as could be seen in Table 1 while, the small hydropower (SHP) accounts for mere 734 MW of electricity.

Table 1: Nigerian Electricity Generating Mixtures

Company	Type	Capacity
Kainji/Jebba Power Plc	Hydro	1,330MW
Ughelli Power Plc	Gas	942MW
Sapele Power Plc	Gas	1,020MW
Shiroro Power Plc	Hydro	600MW
Afam Power Plc	Gas	987.2MW
Niger Delta Power Holding Company	Gas	5,455MW
IPP's	Gas	1,392MW
Egbin Power Plc	Thermal	1,320MW

Source: Nigerian Electricity Regulatory Commission (NERC, 2015).

Other sources of RE in Nigeria include wind energy with a potential of 150,000 terra joule per year, generated by an average wind speed of 2.0–4.0 m/s, solar radiation estimated at 3.5–7.0 kWh/m^2, and biomass at 144 million tons per year. Unfortunately, most of these other sources of RE are yet to be fully exploited for rural electrification (Agbetuyi *et al*., 2012). According to Nigeria Renewable Energy Master Plan, 2011, the country seeks to increase the supply of electricity from renewable energy systems to 36% by 2030 (Akorede *et al*., 2017). The economic policy that is in force in the country aims at encouraging the distribution locations to procure at least 50% of their electricity from renewable sources. Another target set in the country's REMP is to increase the electrification rate from about 40% to 75% by 2025 (IRENA, 2019). Therefore, in this paper, the proposed framework was applied to Nigeria distribution locations with the aim of deciding the amount of required renewable energy installations to support the existing power capacity and hence to provide adequate power production while optimizing the use of renewable energy systems.

2. Methodology

Optimization is a quantitative procedure that requires the application of discipline and serious multivariable mathematical technology (Amosun and Muhammed, 2021). Hence, this section is devoted to the problem setup and related descriptions, the aim is to develop a general framework that will be used to determine the optimal total capacities of renewable energy sources (solar and wind) to be installed in different locations in the country, in order to increase the amount of renewable energy installations so that the power supply could be comparable to the peak power demand in the country. This was done by designing an optimization problem that minimizes the total cost of installing RESs that will be used to support the existing installed power capacity (Aliyu and Tekbiyik-Ersoy, 2019). Constraints of the designed optimization problem includes; demand and supply, renewable energy potentials. The optimization problem formulation in this study is divided into off-grid which accesses electricity level below 50%, on-grid which accesses electricity level above 50% and all-off-grid which finds the optimal cost of installing off-grid renewable energies

2.1 Linear Programming Model Formulation

The linear programming model was formulated based on three basic components as reported elsewhere (Ajayi, 2009):

1. Decision variables to be determined,
2. Objective (goal or aim) to optimize,
3. Constraints that need to be satisfied.

The parameters, variables and constraints were determined according to the notations thus:

i = Location
j= Technology
X*ij*WT = Prospective installed capacity of the worst renewable energy technology in location, '*i*'
X*ij*BT = Prospective installed capacity of the best renewable energy technology in location, '*i*'
X*i*WL*j* = Prospective installed capacity of technology, '*j*' in the worst locations for Technology, '*j*'
XiBL*j* = Prospective installed capacity of technology, '*j*' in the best locations for Technology, '*j*'
ICT = Total installed cost in ₦
X*ij* = Renewable energy capacity for technology, '*j*' to be installed in location, '*i*'
A*ij* = Area required (km^2) to install 1 MW of technology, '*j*' in location 'i'
C*j* = Cost of installing 1MW of technology. '*j*' in ₦/MW
WT*i* = Worst technology in location, '*i*'
BT*i* = Best technology in location. '*i*'
WL*j* = Worst location for technology, '*j*'
BL*j* = Best location for technology, '*j*'

2.1.1 Assumptions on the Linear Programming Technique

Some of the assumptions made for the Linear Programming technique applied in this research work as related to the optimization problem are as follows.

1. The effective power demand is to be met by the existing plants (generations) and new renewable generation,
2. The off-grid installation constraints satisfy the demand and supply constraints,
3. The on-grid installation constraints satisfy the demand and supply constraints,
4. There are systems reserve (*SR*) requirements which must be satisfied to guarantee reliability of the system.
5. The system reserve (*SR*) constraints for both off-grid and on-grid plants were assumed to be 10%,
6. The application in locations with electricity access level at 50% or above were preferred to be on-grid while those below 50% were preferred to be off-grid.

2.1.5 Limitations and constraints

The constraints that limit what is obtainable and also serve as conditions on which the optimization problem rests are as follow:

1. There is demand-supply limitation
2. There is off-grid installation limitation
3. There is an on-grid installation limitation

2.2 Model Development

2.2.1 Objective Function

The main objective of this study is to find the minimum cost of installing RE technologies in various locations while satisfying pre-determined constraints. The problem was mathematically formulated as a linear optimization (minimization) problem with the objective function shown in equation 1 as reported by Akpan (2015); Aliyu and Tekbiyik-Ersoy (2019) and Abraham (2021).

Minimize:

$$\text{ICT}=\sum_{j=1}^{m} C_j \sum_{i=1}^{n} X_{ij} \quad (1)$$

Total installation cost = Cost of installing 1MW × Prospective installed capacity (2)

Cost of installing 1MW = $\sum_{j=1}^{m} C_j$ (3)

Prospective installed capacity = $\sum_{i=1}^{n} X_{ij}$ (4)

where: ICT = Total installation cost in ₦, C_j is the cost of installing 1MW of technology, '*j*' in ₦/MW, Xij is the renewable capacity for technology, '*j*' to be installed in location,' *i*' (prospective installed capacity), where *i* = 1 . . . *n* and *j* = 1 . . . *m*.

2.2.2 Demand and Supply Constraints

The effective power demand is to be met by the existing plants and new RE generation. This involves the following set of constraints for the prospective RE capacities:

i. Prospective off-grid installation constraints: The demand and supply constraints for off-grid installation locations are expressed in equation 5.

$$\sum_{j=1}^{d} CF_{ij}X_{ij} \geq ED_i - PS_i \quad (5)$$

where: CF_{ij} is the capacity factor in percentage (%) for technology, '*j*' in location, '*i*', and *i* = 1 . '*d*' is the number of off-grid installation locations. PS_i is the current power supply to each off-grid installation location, '*i*' in MW, and *EDi* is the estimated demand in MW for each off-grid installation location, '*i*' in order for the electricity access level to be 100% (Akpan, 2015).

ii. Prospective on-grid installation constraints: To satisfy the on-grid demand and supply constraints, equation (6) was formulated (Aliyu and Tekbiyik-Ersoy, 2019)

$$\sum_{j=1}^{m} \sum_{i=d+1}^{n} CF_{ij}X_{ij} \geq (RPD - PD_e) - (RPS - \sum_{i=1}^{d} PS_i) \quad (6)$$

where: *RPD* and *RPS* are the reported power demand and total power supply in MW for the region of analysis respectively, and PD_e is the total estimated power demand of the off-grid installation locations in MW (Aliyu and Tekbiyik-Ersoy, 2019).

2.2.3 System Reserve Requirements

To guarantee reliability of the system, the system reserve (SR) must be satisfied. SR is expressed in percentages (%), and can be defined as an additional and base component of load demand. Hence, the SR requirement is expressed by equations 7 and 8 (Aliyu and Tekbiyik-Ersoy, 2019).

i. Prospective off-grid reserve constraints: The off-grid SR requirement was calculated using equation (7). It should be noted that the SR requirement is an additional amount of electricity that is used in supporting the actual load demand requirement. In most cases it is about 10% of the actual demand (Aliyu and Tekbiyik-Ersoy, 2019).

$$\sum_{j=1}^{m} CF_{ij}X_{ij} \leq (1 + SR)(ED_i - PS_i) \quad (7)$$

ii. Prospective on-grid reserve constraints: The SR requirement related with on-grid installations was formulated from equation 8 (Aliyu and Tekbiyik-Ersoy, 2019).

$$\sum_{j=1}^{m} \sum_{i=d+1}^{n} CF_{ij}X_{ij} < (1 + SR)[(RPD - PD_e) - (RPS - \sum_{i=1}^{d} PS_i)] \quad (8)$$

2.2.4 Area constraints

The area required to install the RESs in a given location was calculated by using equation 9 (Aliyu and Tekbiyik-Ersoy, 2019; Amosun and Muhammed, 2021).

$$\sum_{j=1}^{m} A_{ij} \sum_{i=1}^{n} X_{ij} \quad (9)$$

where: A_{ij} is the area required (km²) to install 1 MW of technology, '*j*' in location '*i*', '*Xij*' is renewable energy capacity for technology, '*j*' to be installed in location, '*i*'.

2.2.5 Natural constraints

The natural constraints of the decision variables are expressed according to equation 10 (Amosun and Muhammed, 2021).

$$X_{ij} \geq 0 \tag{10}$$

The installation costs for off-grid solar and wind used in the study was ₦1,091,136,240 and ₦1,641,737,680 per KW respectively. While the on-grid solar and wind installation costs used in the study was ₦886,302 and ₦1,026,797,280 per KW respectively, as shown in Table 2.

Table 2: Installation costs and system sizes for photovoltaic (PV) and wind technologies

Technology Type	Mean Installed Cost (₦/Kw)	Size (acres/MW)
PV < 10KW	1,705,638,960	3.2
PV 10 – 100KW	1,515,685,840	5.5
PV 100 – 1000KW	1,091,136,240	5.5
PV 1 – 10KW	886,302	6.1
Wind < 10KW	3,346,063,600	30
Wind 10 – 100KW	2,677,726,240	30
Wind 100 – 1000KW	1,641,737,680	30
Wind 1 – 10KW	S1,026,797,280	44.7

Source: National Renewable Energy Laboratory (NREL, 2018).

The average electricity access level and the preferred application type for each distribution location are shown in Table 3. The application type (on-grid or off-grid) was chosen based on the average electricity access level of each location. The applications in locations with electricity access level at 50% or above were preferred to be on-grid while those below 50% were preferred to be off-grid. However, it should be noted that 50% is just a threshold selected for this study but can easily be changed according to the requirements of energy planners.

Table 3: Average electricity access levels and preferred distribution locations

S/N	Distribution Locations	Access Level (%)	Preferred Application
1	Abuja	56	On-grid
2	Benin	67	On-grid
3	Eko and Ikeja	99	On-grid
4	Enugu	65	On-grid
5	Ibadan	75	On-grid
6	Jos	34	Off-grid
7	Kaduna	41	Off-grid
8	Kano	36	Off-grid
9	Port Harcourt	61	On-grid
10	Yola	25	Off-grid

Source: Adapted from (Akpan, 2015).

2.3 Sensitivity Analysis

Sensitivity analysis is always applied to explore the accuracy and robustness of the model results under uncertain conditions. The sensitivity analysis performed in this paper was carried out by varying the installation costs of both on-grid and off-grid arrangements for the solar and wind technologies. To minimize the total cost, it is assumed that all the distribution locations are off-grid so as to determine the optimal renewable energy systems allocation. The sensitivity analysis data for the prospective installed capacities are presented in Table 4 below.

Table 4: Sensitivity analysis data for off-grid arrangement

Distribution Location	Prospective Total Installed Capacity (MW)	Prospective Installed Solar Capacity (MW)	Prospective Installed Wind Capacity (MW)	Average Generation (MW)
Abuja	11,789.75	6,155.43	5,634.32	1,920.55
Benin	9,760.08	5,192.36	4,567.72	1,200.49
Eko and Ikeja	8,495.19	4,757.31	3,737.88	1,626.83
Enugu	7,276.63	3,485.51	3,791.12	1,246.65
Ibadan	7,513.95	3,839.62	3,659.33	1,502.79
Jos	7,444.65	3,853.28	3,591.37	1,623.64
Kaduna	7,721.45	4,130.08	3,591.37	1,623.64
Kano	8,542.08	4,130.08	4,412.00	2,215.69
Port Harcourt	5,900.67	3,854.65	2,046.02	973.61
Yola	7,721.45	4,130.08	3,591.37	1,851.65
Total	82,165.90	-	-	15,785.54

The main purpose for the off-grid arrangement for all the distribution locations was to supply the demand-supply gap of each distribution location by using the prospective installations only in that distribution location.

3.0 Results and Discussion

3.1 Optimal Capacities at Different Installation Locations

In order to minimize the total cost for prospective off-grid arrangement, all the distribution locations with electricity access level below 50% are taken into consideration so as to determine the optimal renewable energy set up allocation. The prospective installed capacities are the optimal capacities to be installed for each technology in each location. Table 5 shows the wind and solar related Capacity Factors (CFs) for each distribution location. The Capacity Factors for each distribution location were done by calculating the capacity Factors of all the available locations within each distribution location and finding the average. It could be observed that wind has a better capacity factor when compared with solar in Nigeria. Also Kano and Benin has the highest and lowest wind and solar capacity factors respectively.

Table 5: Wind and solar capacity factors in % for each distribution location

S/N	Distribution Location	Wind Energy Capacity Factor (%)	Solar Energy Capacity Factor (%)
1	Abuja	17.50	15.09
2	Benin	10.00	14.60
3	Eko and Ikeja	23.00	15.30
4	Enugu	18.80	15.00
5	Ibadan	21.00	19.00
6	Jos	23.00	20.70
7	Kaduna	26.00	21.10
8	Kano	28.00	21.60
9	Port Harcourt	16.00	17.00
10	Yola	27.00	21.26

Source: IRENA, 2017. https://www.iea.org/energyaccess accessed on 20 December, 2018.

The simulation results for the prospective installed capacities are presented in Table 6. The optimization results for off-grid arrangement indicate that in Jos, the optimization results show that 3,853.28MW of the installations should be solar while wind's share is 3,591.37MW. Again, the solar and wind shares in Kaduna are found to be 4,130.08MW and 3,591.37MW respectively. Similarly, for Kano, the optimization revealed that 4,130.08MW and 4,412.00MW of the installation is assigned to solar and wind respectively. Solar and wind represent 4,130.08MW and 3,591.37MW respectively of the installations for Yola. The prospective total installed capacity of all the off-grid arrangement distribution locations was found to be 31,429.63MW while the total average power generation was found to be 7603.92MW. In addition, the optimal total cost of installing renewable energy systems in all the off-grid arrangement distribution locations was found to be ₦97.46billion.

Table 6: Optimal capacities and generation for prospective off-grid arrangement

Distribution Location	Prospective Total Installation Capacity (MW)	Prospective Installed Solar Capacity (MW)	Prospective Installed Wind Capacity (MW)	Average Power Generation (MW)
Jos	7,444.65	3,853.28	3,591.37	1,623.64
Kaduna	7,721.45	4,130.08	3,591.37	1,912.94
Kano	8,542.08	4,130.08	4,412.00	2,215.69
Yola	7,721.45	4,130.08	3,591.37	1,851.65
Total	31,429.63	-	-	7,603.92

Since the distribution locations have substantial level of electricity access, the installation does not have to cover the supply and demand gap at each and as such, only the total gap should be supplied. The simulation results for the prospective installed capacities are presented in Table 7. The optimization result revealed that Abuja and Port Harcourt are allocated 22,564.89MW each of the proposed installed capacity.

Table 7: Optimal capacities and generation for prospective on-grid arrangement

Distribution Location	Prospective Total Installed Capacity (MW)	Prospective Installed Solar Capacity (MW)	Prospective Installed Wind Capacity (MW)	Average Generation (MW)
Abuja	22,564.89	2,256.89	0	3,404.82
Benin	1,427.28	1,427.28	0	208.38
Eko and Ikeja	3,254.20	1,627.10	1,627.10	662.23
Enugu	2,724.81	1,427.28	1,297.53	445.05
Ibadan	3,054.38	1,427.28	1,627.10	580.05
Port Harcourt	22,564.89	22,564.89	0	3,610.38
Total	55,590.45	-	-	8,910.91

The prospective installed capacities for Benin, Eko and Ikeja, Enugu, Ibadan, are 1427.28MW, 3254.20MW, 2724.81MW and 3054.38MW respectively. However, the prospective installed wind capacity for Abuja, Benin and Port Harcourt are zero due to the poor wind potential in those distribution locations. Hence, the prospective total installed capacity of all the on-grid arrangement distribution locations was found to be 55,590.45MW while the total average power generation was found to be 8910.91MW. It is imperative to remark that this result is consonant with the target estimated in the country's REMP, which highlights that 50% of each DISCO's purchase should come from renewable. In addition, the total cost of installation was found to be ₦49,908,650,400.

The sensitivity analysis results for all-off-grid revealed that in Abuja, solar should be favored since the results show that 6155.43MW of the installations should be solar while wind share is

5634.32MW. For Benin, solar and wind shares are found to be 5192.36MW and 4567.72MW respectively. For Eko and Ikeja, the analysis result revealed that 4757.31MW and 3737.88MW of the installation is assigned to solar and wind respectively. For Enugu, it is found that solar and wind shares represent 3485.51MW and 3791.12MW respectively. For Ibadan, the results show that 3839.62MW and 3659.33MW of the installation was assigned to solar and wind respectively. Again, in Port Harcourt, 3854.65MW and 2046.02MW of installations should be allocated to solar and wind respectively. In Jos, solar should be favored, as the analysis result revealed that 3853.28MW of the installations should be solar while wind shares 3591.97MW. For Kaduna, the solar and wind share represents 4130.08MW and 3591.97MW respectively. For Kano, the analysis results show that 4130.08MW and 4412.00MW of the installation is allocated to solar and wind respectively. Lastly, for Yola, solar and wind are found to be 4130.08MW and 3591.37MW of the installations respectively. It is noteworthy that for the off-grid arrangement for all the distribution locations, the renewable energy installation is designed such that each distribution location can generate its own power. Moreover, the prospective total installed capacity of all the off-grid setup distribution locations was found to be 82,165.90MW while the total average power generation was found to be 15,785.54MW while the optimal total cost of installing renewable energy systems in all the off-grid setup distribution locations is found to be ₦106,938,354,400.

The sensitivity on the installation cost is based on wind and solar technologies' installation costs. Table 6 shows all the associated cost values and sensitivity analysis-related cases. The cases are +10%, +20%, +30%, -10%, -20% and -30% change in wind technology installation cost only (keeping solar-related cost constant), and solar technology installation cost only (keeping wind-related cost constant).

Table 6: Sensitivity variables and corresponding values

Sensitivity Variable	Installation Cost (₦/KW)		SD of Installation Cost (%)
	On Grid	Off Grid	
Solar	886,302	1,091,136,240	±10, ±20, ±30
Wind	1,026,797,280	1,641,737,680	±10, ±20, ±30

The sensitivity analysis of change in technology-related costs and total installation costs for off-grid and on-grid arrangements are presented in Figures 1 and 2 respectively. The results showed that decrease in the wind technology costs will significantly reduce the total installation cost in the case of off-grid arrangement (rather than the case of having a decrease in solar energy-related costs) while the on-grid total installation costs can be decreased more when the cost associated with installing solar technology is reduced (rather than the case of having a decrease in wind energy-related costs).

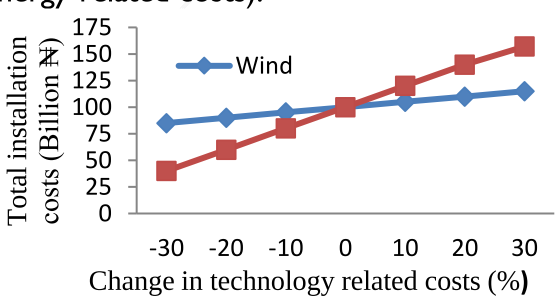

Figure 1: Sensitivity analysis of change in technology-related cost and total installation cost for off-grid arrangement.

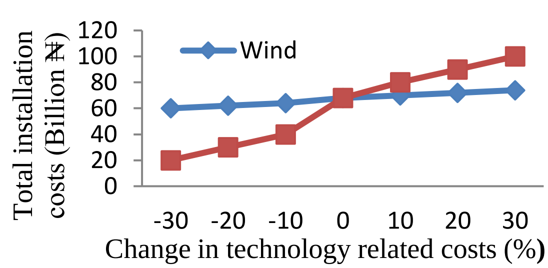

Figure 2: Sensitivity analysis of change in technology-related costs and total installation cost for on-grid arrangement.

The results obtained show that wind is not viable in some parts of the country due largely to the low potential of wind energy especially in the southern part of the country. The results of the sensitivity analysis revealed that the cost associated with on-grid renewable energy system can be reduced considerably by reducing the installation cost of solar energy technologies. On the other hand, for off-grid arrangement, the analysis reveals that the government and other stakeholders in the energy sector should focus more on policies geared towards reducing the cost of installing wind energy technology. Since the government alone can't sufficiently fund such projects that are capital intensive, Nigerian government should as a matter of urgency identify and develop clear policy incentives for increased private sector participation in the delivery of renewable energy (Eleri *et al*., 2012). For developing countries such as Nigeria to improve upon her electricity access, security and sustainability, especially in the rural areas, renewable energy utilization has to be encouraged through proper planning by incorporating strategies such as Supply-Side Management (SSM), and implementation of effective policies (Szabo *et al*., 2011). Optimization has been one of the methods deployed to achieve proper planning in electricity sector more so when it has to do with renewable energy installations.

4.0 Conclusion

The flexibility of the framework and models used in this paper were carefully taken into consideration so as to guarantee the possibility of using them in different regions and areas. It ensures the increased use of renewable energy systems such as wind and solar in combination with existing generation capabilities as used in the case study. The proposed optimization model was developed based on linear programming through which the minimum costs of installing renewable energy systems for three different arrangements (off-grid, on-grid and all-off-grid) were determined. It was deduced that the proposed models were successful in minimizing the total installation costs of renewable energy (wind and solar) by considering the best renewable energy technologies in each location and avoiding extra installations. Notwithstanding the fact that, Nigeria is generally blessed with ample conventional and renewable energy resources, the demand is significantly higher than the energy generated. Due to the abstruse inefficiencies associated with electric energy provision in Nigeria, it is increasingly harder for rural Nigerians to have access to the electricity service. This paper is advocating the use of renewable energy resources for closing the gap between energy demand and supply in Nigeria as well as improving the wellness of rural Nigerian communities. The potential of various renewable energy sources including large and small hydropower systems, solar energy and wind energy were elaborated. Many of the government of Nigeria energy initiatives are merely paper policies that lack the political will to take it to the implementation realm. Even though it may be difficult to navigate the intricacies of Nigeria's energy governance tumult, a fine line of argument is straddled throughout this research work. By avowing that existing government policies are ineffective, some new measures that can meld well with these policies to reinvigorate them such as supply-side management (SSM) and implementation of effective policies were proposed. A careful look at the results shows that incorporating renewable energy in Nigeria's power generation is vital in resolving the current power problem. More so, building solely more on-grid renewable power plants is not enough, rather the system should be supported with off-grid renewable plants to curb the transmission constraints. Furthermore, the study reveals that if the proposed framework is applied in Nigeria, it can help the country to achieve the renewable targets stated in the country's Renewable Energy Master Plan (REMP) which would in turn alleviate the misfortunes of the rural communities currently groaning under acute shortage of electricity.

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