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Optimization of the Industrial use of Renewable Energy for a Sustainable and Hazard-free Environment

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Abstract

The benefits associated with the utilization of renewable energy sources such as improved electricity access, economic development and energy sustainability can never be over-emphasized. Nigeria being a developing country with an acute electricity problem is blessed with renewable energy resources. 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 which include demand and supply, renewable energy potentials. There is inequitable access of rural communities to electricity services in the country as demand supersedes the generation. This paper presents three case scenarios 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 $97.46 and $114.03 billion respectively while that of the third scenario is found to be $244.33 billion. Further analysis of the results obtained revealed that the combination of the off-grid and on-grid installations have the minimum installation cost and it is to be adopted especially in the rural and remote areas.

Keywords: Rural electrification, Cost, Installation, Renewable Energy sources, Linear optimization, Nigeria.

1. Introduction

Renewable energy is energy which comes from natural resources and is also naturally replenished. Renewable sources have been proven to be an efficient and effective solution to increase the availability of energy in isolated zones and reduce energy poverty. According to the Sustainable Development Goals, by 2030, we should be able to provide affordable and clean energy for all. Climate policy occasioned by climate change is changing fast around the world with world leaders raising the call for concerted efforts and deliberate ambitions to reduce greenhouse gas emissions. It is on record that all the forms of alternative energies such as hydroelectric power, wind energy forms, bio fuels, solar energy, fossil fuels all have the potential of discharging new materials into the environment which causes pollution. In parallel to the developing economy, the increase in the energy demand has accelerated the consumption of fossil fuels and greenhouse gas emissions. Under the dual burden of energy and the environment, the world has achieved the consensus of developing renewable energy resources. These resources have the benefits of achieving sustainability and environmental friendliness. The 21st resolutions of the recent United Nations Framework Convention on Climate Change (UNFCCC), Conference of the Parties (COP), outlined promotion of sustainable energy, sustainable management of natural resources and maintaining environmental integrity through the mitigation of greenhouse gas emissions towards sustainable development. Renewable energy is sustainable and natural resource is the source of clean energy. Solar energy is the most abundant and inexhaustible renewable energy resource making the sun's daily radiation to the earth to reach approximately 10,000 times more energy than the average daily energy consumption of the earth. It is worthy of note that harnessing the sun's energy efficiently at a reasonable cost comes as a challenge. The most efficient form of renewable energy includes geothermal energy which is generated by harnessing the earth's natural heat, biomass which has the biggest contribution with 50%, hydroelectricity with 26% and wind power with 18%.

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 agrarians that need electricity to preserve their agricultural produce, they are still being constrained by lack of adequate and reliable electricity. 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 while the small hydropower (SHP) accounts for mere 734 MW electricity.

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, and biomass at 144 million tons per year. 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 2028 (IRENA, 2019). 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 will be elaborated.

Many of the Nigerian government 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 will be 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 will be proposed.

1.1 Statement of the Problem

This research work will focus on three main identified challenges: the environmental, the technical and the financial issues as some of the existing challenges that hinder the production of biomass energy and other forms of alternative energy sources. Although other issues such as social, political and organizational are also the existing challenges that hinder the production of biomass energy, the environmental issue will be the main focus of this research work which will be undertaken to determine and evaluate the impacts that can result from biomass and other alternative energy sources. Considering that the major component of greenhouse gases is carbon dioxide, there is a global concern about reducing carbon emissions. In this regard, different policies could be applied to reduce carbon emissions and other environmental impacts such as enhancing renewable energy deployment and encouraging technological innovations. Furthermore, supporting mechanisms such as feed-in tariffs, renewable portfolio standards and tax policies are usually employed by the government to develop renewable energy generation as well as implementing energy use efficiency for saving energy. However, the environmental challenge is geared towards ensuring the sustainability of renewable energy with regards to the use of the natural resources. Such identified challenges and problems are as given below:

i. The depletion of oil and gas reserve.
ii. The need to reverse the negative impacts of climate change caused by global warming.
iii. The sustainable use of natural resources.

iv. The need to offset the buildup of emissions due to activities involved in biomass.
v. The need to mitigate the effects of greenhouse gas emissions.
vi. The need to advance economic development.
vii. The need to improve access to energy and its security.

2.0 Materials and methods

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 which aims 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 REs 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:

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_{ijBT} = Prospective installed capacity of technology, 'j' in the worst locations for Technology, 'j'
X_iBL_j = Prospective installed capacity of technology, 'j' in the best locations for Technology, 'j'
ICT = Total installed cost in -N-
X_{ij} = Renewable energy capacity for technology, 'j' to be installed in location, 'i'
A_{ij} = Area required (km²) to install 1 MW of technology, 'j' in location 'i'
C_j = Cost of installing 1MW of technology, 'j' in -N-/MW
WT_i = Worst technology in location, 'i'
BT_i = Best technology in location, 'i'
WLj = Worst location for technology, 'j'
BLj = 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 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 installations 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.

2.1.2 Limitations and constraints

The constraints that limit what is obtainable and also serve as conditions 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.

2.1.3 Model development

Component formulation

Total installation cost = Cost of installing 1 MW X Prospective installed capacity

$$\text{Cost of installing 1MW} = \sum_{j=1}^{m} Cj \quad (1)$$

$$\text{Prospective installed capacity} = \sum_{i=1}^{n} Xij \quad (2)$$

2.2 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 (3) as reported by Akpan (2015), Aliyu and Tekbiyik-Ersoy (2019) and Abraham (2021).

Minimize:

$$ICT = \sum_{j=1}^{m} Cj \sum_{i=1}^{n} Xij \quad (3)$$

where ICT = total installation cost in $, Cj is the cost of installing 1 MW 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.

2.3 Constraints

Subject to

2.3.1 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 (4).

$$\sum j{=}1\ CFijXij \geq EDi - PS\mathrm{i} \quad (4)$$

Where CFij is the capacity factor in percentage (%) for technology, ‘j’ in location ‘i’, *and* i = 1. ‘d’ is the number of off-grid installation locations. Psi 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 (5) was formulated (Aliyu and Tekbiyik-Ersoy, 2019).

$$\sum \sum CFijXij \geq (RPD - PDe) - (RPS - d \sum PSi) \quad (5)$$

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).

2.3.2 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 in percentage (%), and can be defined as an additional and base component of load demand. Hence, the SR requirement is expressed by equations (6) and (7), (Aliyu and Tekbiyik-Ersoy, 2019).

i. Prospective off-grid reserve constraints: The off-grid SR requirement was calculated using equation (6). 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).

$$\sum CFijXij \leq (1+SR)\ (EDi - PSi) \quad (6)$$

ii. Prospective on-grid reserve constraints: The SR requirement related with on-grid installations was formulated from equation (7), (Aliyu and Tekbiyik-Ersoy, 2019).

$$\sum \sum CFijXij < (1+SR)\ [(RPD - PDe) - (RPS - \sum PSi)] \quad (7)$$

2.3.3 Area constraints

The area required to install the RESs in a given location was calculated by using equation (8), (Aliyu and Tekbiyik-Ersoy, 2019, Amosun and Muhammed, 2021).

$$\sum Aij\ j=1\ n \sum Xij\ i=1 \quad (8)$$

Where A*ij* is the area required (km²) to install 1MW of technology, 'j' in location 'i', '*Xij*'

is renewable energy capacity for technology, 'j' to be installed in location, 'i'.

2.3.4 Natural constraints

The natural constraints of the decision variables are expressed according to equation (9), (Amosun and Muhammed, 2021).

$$Xij \geq 0 \quad (9)$$

3.0 Result and Discussion

The simulation results for the prospective installed capacities are presented in Table (1) as shown below. 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 3,591.37 MW 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 31,429.63 MW while the total average power generation was found to be 7,603.92 MW. In addition, the optimal total cost of installing renewable energy systems in all the off-grid arrangement distribution locations was found to be $97.46 billion.

Table 1: Optimal capacities and generation for prospective off-grid arrangement

Distribution Location	Prospective Total Installed Capacity (MW)	Prospective Installed Solar Capacity (MW)	Prospective Installed Wind Capacity (MW)	Average Power Generation (MW)
Jos	7444.65	3853.28	3591.37	1623.64
Kaduna	7721.45	4130.08	3591.37	1912.94
Kano	8542.08	4130.08	4412.00	2215.69
Yola	7721.45	4130.08	3591.37	1851.65

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

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 (2). The optimization result revealed that Abuja and Port Harcourt are allocated 22,564.89MW each of the proposed installed capacity.

Table 2: 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	2256.89	2256.89	0	3404.82
Benin	1427.28	1427.28	0	208.38
Eko and Ikeja	3254.20	1627.10	1627.10	662.23
Enugu	2724.81	1427.28	1297.53	445.05
Ibadan	3054.38	1427.28	1627.10	580.05
Port Harcourt	22,564.89	22,564.89	0	3610.38

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

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 cost 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 (3) above while sensitivity variables and their corresponding values are shown in Table (4) below.

Table 3: Sensitivity analysis 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	6155.43	5634.32	1920.55
Benin	9760.08	5192.36	4567.72	1200.49
Eko and Ikeja	8495.19	4757.31	3737.88	1626.83
Enugu	7276.63	3485.51	3791.12	1246.65
Ibadan	7513.95	3839.62	3659.33	1502.79
Jos	7444.65	3853.28	3591.37	1623.64
Kaduna	7721.45	4130.08	3591.37	1623.64
Kano	8542.08	4130.08	4412.00	2215.69
Port Harcourt	5900.67	3854.65	2046.02	973.61
Yola	7721.45	4130.08	3591.37	1851.65

It is worthy of note that the installed capacity is the expected optimal performance of the Renewable energy source. Average Capacity is the available performance that the Renewable energy source can be able to deliver at a particular point in time due to some external interferences and unforeseen circumstances.

Table 4: Sensitivity variables and corresponding values

Sensitivity Variable	Installation Cost ($/Kw)		SD of Installation Cost (%)
	On-Grid	**Off-Grid**	
Solar	2025	2493	±10, ±20, ±30
Wind	2346	3751	±10, ±20, ±30

The results presented 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. 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. 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

In this research work, 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 provide adequate power production while optimizing the use of renewable energy systems for a sustainable and hazard-free environment. 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 (0ff-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.

The off-grid installation arrangement results show that the optimal total installed capacities for related distribution locations such as Jos, Kaduna, Kano and Yola are 7444.65MW, 7722.45MW, 8542.08MW and 7721.45MW respectively. Conversely, in the on-grid installation arrangement, the optimal installations for each distribution location are found to be 22,564.89MW, 1427.28MW, 3254.20MW, 2724.81MW, 3054.38MW and 22,564.89MW for Abuja, Benin, Eko and Ikeja, Enugu, Ibadan and Port Harcourt respectively. In addition, the total installation costs of the first and second arrangements (that include having off-grid installations for some distribution locations and having on-grid installations for other distribution locations) are $97.46 billion and $114.03 billion respectively with a total cost of $211.49 billion. Conversely, the result of third installation arrangement (only off-grid installation for all distribution locations) is found to be $244.33 billion. 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).

5.0 Recommendations

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. 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. 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.

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Nomenclature

RE = Renewable Energy,
BHP = Big hydropower,
SHP = Small hydropower
IRENA = International Renewable Energy Agency,
NERC = National Electricity Regulatory Commission,
DISCOs = Distribution Companies,
TCN = Transmission Company of Nigeria.

Declaration of Generative AI and AI-assisted technologies in the writing process

There were no Generative AI and AI-assisted technologies in the writing process. However, the authors made the following contributions and take responsibility for such.
C. O. Njoku: Conceptualization, Methodology, Investigation and Data curation.
A. V. Gambo: Conceptualization Methodology, Validation and Writing.
U. E. Uche: Supervision, Reviewing and Editing.
Y. Bello: Conceptualization, Methodology, Validation and writing.
R. E. Donatus: Conceptualization, Methodology, Validation and Writing.

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