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Research Article

Modeling renewable energy integration for Nigeria's 2030 electricity target using EnergyPLAN

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Abstract: Nigeria struggles to meet its energy needs due to old infrastructure, poor grid management, frequent power outages, and other reasons, despite its rich fossil fuel reserves. The integration of renewables such as solar, wind, and hydro energy sources is a major solution. Renewables can assist Nigeria in diversifying its energy mix, reducing fossil fuel use, and improving electricity availability, especially in off-grid rural areas. Renewable energy reduces the electricity gap and helps the government meet its environmental and economic goals. This work uses EnergyPLAN to model the integration of wind, solar, hydro, and biomass technologies with natural gas-fired power plants to fulfill the 2030 goal of 30 GW with 30% renewable energy. Nine scenarios were created to fulfill the goal. The analysis shows that the natural gas-fired power plant with hydropower generates the highest electricity from RES with 26.5%. The lowest overall investment cost and annual cost are 18.4 billion dollars and 2.47 billion dollars for a natural gas-fired power plant and a solar PV facility, respectively. Scenario 9 has the integration of NG with solar PV, wind, hydropower, and biomass, emerged as the optimal scenario, yielding the lowest CO_2 emissions (8.97 Mt CO_2/yr), a 26.4 % RES share, and an estimated payback period of 3 years. Its total investment cost (32.9 B USD) and annual cost (4.36 B USD), provide both environmental and economic advantages. This study shows how to reach Nigeria's 2030 electricity targets.

Keywords: *Electricity, Energy sources, Renewable, Vision 30-30-30*

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Nomenclature

Abbreviations	**Descriptions**
CO2	Carbon dioxide
GHG	Green House Gas
GW	Gigawatts
KWh	Kilowatts-hour
MW	Megawatts
NG	Natural gas
PV	Photovoltaic
RES	Renewable Energy Source
R-NG	Reference scenario with NG
USD	United State Dollars
TWh	Terawatts-hour

1. INTRODUCTION

Nigeria, in response to the global imperative of transitioning from conventional energy sources towards clean and sustainable energy sources, has set targets to bring changes to its energy sector. This transformative journey spans across energy security, economic growth, and environmental sustainability. The plan to address the country's energy challenge is to increase the country's power generation capacity, and that involves investing in renewable energy sources, which, according to [1], includes long-term goals: The first being the expansion target of installing 30 GW on-grid capacity by 2030, of which 13.8 GW is attributed to renewables, and the second goal is universal electrification by 2040. In the bid to increase the country's electricity generation capacity by 30 GW by 2030, several issues need to be addressed. Nigeria's current electricity generation capacity is 12.5 GW, total installed generation capacity (of which 3.5–5.0 GW is operationally dispatched daily) and 7,500 MW transmission capacity, with an estimated 150 kWh yearly electricity usage per capita [2].

The Nigerian electricity sector faces numerous challenges, which include inadequate infrastructure, corruption, vandalism, and poor maintenance, which have all contributed to the poor generation and distribution of electricity in the country. The proposed solution to Nigeria's power generation problem by Ref. [3] suggests the traditional six Generation Companies (GenCos) along with the National Integrated Power Project (NIPP) installations, which are both federally owned power plants, are integrated into the national electricity grid. Independent power plants should have the option to directly sell electricity to states or through the national grid facilitated by the Nigerian Bulk Electricity Trading Plc (NBET) [4].

According to a review of Africa's energy supply through renewable energy production by Ref. [5], Nigeria's renewable energy generation amounts to 2,079 MW, marking a substantial portion of the country's total power production capacity, which stood at 7,500 MW. However, despite this significant renewable energy contribution, the predominant source of energy for consumption in Nigeria remains fossil fuel generators, contributing to a loss in economic productivity due to inconsistent power supply as detailed by Ref. [6] in the research on economic cost and environmental impact of fossil fuel dependency in sub-Saharan Africa with Nigeria as a case study, the research result noted that end-users of gasoline generators in Nigeria spend 48 % (ca. USD 99 or ₦35,727) of their monthly (ca. USD 207 or ₦74,702) income on generators for electricity and the yearly Green House Gas (GHG) emissions on generator fleet in the most populated state in Nigeria, Lagos is 1.5 million CO2e.

The need to shift dependency on fossil fuel generators to renewable energy sources is paramount in order to meet renewable energy targets and also reduce carbon emissions. There are other benefits tied to transitioning to renewables, which include job creation, enhanced environmental stability, energy access and affordability, infrastructure development, and economic diversification. One of the projects leading to achieving this renewable goal is the "Vision 30-30-30 project" announced by the Nigerian government in 2016, which is a set target of raising electricity power generation to 30 GW capacity by the year 2030 with a minimum renewable energy share of 30% [7]. At the 7th Nigerian Energy Summit, 2022, themed "Energizing Economic Growth & Sustainability," the Federal Government of Nigeria reassured its commitment to achieving its set goals in 2030 [8]. Hence, the novelty of this study is based on the proposed sustainable solutions to solving Nigeria's energy poverty, meeting its set Renewable Energy Source (RES) share target in the year 2030, as well as its perceived impact on economic growth and environmental sustainability. Most modeling efforts and studies for Nigeria have largely omitted hourly, system-wide scenario comparisons and have not assessed combined multi-RES portfolios on an annual basis. This study of a nine-scenario, EnergyPLAN-based analysis helps to fill this gap. To the authors' best knowledge, no previous study has focused on providing different scenarios to meet the target with different combinations of renewable energy sources on an hourly basis for a complete year.

The remainder of this paper is organized as follows: Section 2 reviews the literature; Section 3 describes methods; Section 4 presents results and discussion; and Section 5 concludes with policy implications.

2. LITERATURE REVIEW

Numerous studies have established a positive correlation between the adoption of renewable energy technologies and technical and economic growth. A study by Ref. [9] looks at the chances of China reaching its 2030 energy and climate policy goals amidst various uncertainties. The authors applied an energy economy environment integrated model. One notable key finding from the study is that without additional policies, the chances of meeting these targets are low, with a focus on carbon emission peaking and non-fossil energy development as well as carbon pricing, which is important for stopping pollution. The research says it's easier to reduce carbon pollution, but it's harder to reach goals for when carbon pollution stops increasing and for using non-fossil fuel energy and Ref. [10] highlighted that China still faces multiple interrelated uncertainties around economic growth, energy efficiency, renewable energy deployment, electrification, carbon capture storage, policy implementation, and technological advancements that will collectively determine its ability to meet its 2030 energy and climate goals. With the aims of reducing GHG emissions in Wallonia, Belgium, Ref. [11] took a look into the strategies and implications for Wallonia to reduce its GHG by 55% by 2030. The Walloon Region plans, according to Ref. [12], to significantly increase its share of renewable energy sources, particularly solar and wind power, to reduce its reliance on fossil fuels. The research findings indicate that the feasibility of achieving the −55% GHG target by 2030 is possible with just a 0.5% increase in total system costs in comparison to an unconstrained reference scenario, and according to updates made in the recent Belgian National Energy and Climate Plan in Ref. [13], this target is in line with the European Union's goal of reducing emissions by at least 55% by 2030 under the European Green Deal.

Saudi Arabia also has Vision 2030 targets for renewable energy. Ref. [14] examines the necessary circumstances alongside the resources that Saudi Arabia needs to meet its Vision 2030 targets for renewable energy. The study focuses on the input requirements needed for the production of solar and renewable energy, such as mineral production and human capital. The potential economic, social, and external impacts of converting Turkey’s power system to affordable renewable energy sources by 2030 were assessed by Ref. [15]. The study shows that 55% of Turkey’s electricity needs could be met by renewable energy sources by 2030. Energy efficiency can lower the overall power demand in Turkey by 10% when compared to the case of business as usual. The authors noted that an important tool to accomplish these goals and reduce emissions from the electricity industry is the introduction of a carbon fee. Ref. [16] suggested that Turkey needs to revise the 2030 targets from 32% to at least 50%, emphasizing Turkey's potential to significantly enhance its renewable energy capacity. The Spanish government's National Integrated Energy and Climate Plan (NIECP), aims to bring about significant expansion to PV capacity by 2030. Refs. [18,17] highlight that there will be a need for substantial energy storage and fast-ramping backup power to manage variability and avoid curtailing excess solar energy.

With Nigeria as a case study, Ref. [19] came about a comprehensive strategy to achieve 100% electrification in Nigeria by adopting a mix of renewable and non-renewable energy sources. The study explored 99 different scenarios, for each scenario, accessing economic feasibility, carbon emissions, and capacity to meet Nigeria's projected electricity demand of 200 TWh/year by 2030. The research finding shows that an energy mix of natural gas with renewables like photovoltaic or onshore wind power is the most sustainable and cost-effective approach, and the research concludes that Nigeria achieving a 100% electrification target will require a lot of investment alongside renewable energy integration, balancing renewables with natural gas to ensure reliability and sustainability in Nigeria's power supply. The challenges and prospects of Nigeria’s renewable energy transition were explored by Ref. [20] using lessons from other countries’ experiences. The study emphasizes how crucial it is to have a fair and sustainable energy transition to meet the Sustainable Development Goals (SDGs) of the UN by 2030. Using examples from the successful energy transitions of other emerging nations, the article emphasizes the necessity of comprehensive energy reforms. Accessing Nigeria's energy transition pathway, [1] offers transitional strategies to achieve the country's goals for decarbonization, renewable energy, and access to electricity. Examining the aforementioned countries with analogous 2030 objectives—Belgium aims to reduce GHG emissions by 55%, Turkey seeks to enhance RES integration to at least 50%, and both Saudi Arabia and Spain intend to substantially increase their RES penetration; these nations, in comparison to Nigeria, possess greater electricity access and more ambitious targets. Nonetheless, all are progressing towards improved renewable energy integration.

The current literature on Nigeria's renewable energy planning and scenario modelling is primarily focused on technical and economic projections, often neglecting the critical social, institutional, and regulatory factors that affect sustainable energy transitions. Many studies rely on static assumptions and limited, sometimes outdated, data, which hampers their ability to accurately reflect the complexities of Nigeria's energy landscape. Characterized by widespread energy poverty and the need for decentralized, off-grid solutions. This gap in data and analysis limits the effectiveness of models in capturing uncertainties such as political instability and inconsistent policy implementation, which are necessary in shaping Nigeria's renewable energy future.

Nigeria's energy planning issues are several and include an antiquated, unstable system, great reliance on fossil fuels in spite of notable renewable potential, and a lack of consistent data, all worse by political instability and uneven policy execution. In contrast, other developing nations like Kenya and South Africa have used more consistent regulatory systems, distributed energy solutions, and focused incentives to draw private investment and increase access to renewable energy, stressing the need for Nigeria to take a more integrated and coordinated approach to address its energy planning challenges.

Literature involving energy transition, GHG emissions, and renewable energy integration highlights the need for substantial investment in achieving these energy targets, suggesting that Nigeria's 30-30-30 target can be technically and economically attainable with the correct policy backing, financial investments, and concerted efforts, Ref. [20] indicates, even though it will be a substantial challenge. The aim of this study is essential to Nigeria's overall energy transition and development strategy since its successful implementation could boost the nation's economic growth and environmental sustainability.

3. METHODS AND MATERIALS

The technologies used in this research are those mostly used globally and also in Nigeria, which comprise a natural gas-fired thermal plant, a biomass power plant, hydropower, onshore wind, a photovoltaic system, and a hydro storage system, in which the energy resources considered are natural gas, wind, solar, hydro, and biomass.

3.1. EnergyPLAN Simulation Tool

The program includes a phase for coordinating a complete case study of the power, heating, and transportation sectors. This application is critical for researching and modeling future energy systems since it allows for a comparative analysis of different energy configurations and hourly simulations of regional energy systems. To do this, the EnergyPLAN model is used, which examines and determines the ideal mix of energy technologies for a certain location based on numerous variables, including:

- *Carbon dioxide emissions:* Quantifying greenhouse gas outputs to assess environmental impacts.
- *Primary energy supply:* Encompassing total fuel consumption and the energy equivalence of non-fuel-based energy sources.
- *Excess power generation:* Representing surplus electricity that can potentially be exported.

- *Fossil fuel dependency and renewable energy share:* Assessing the proportion of energy derived from renewable sources relative to fossil fuels.
- *Production mix across primary energy sources:* Evaluating the contributions of diverse energy inputs.
- *Socioeconomic and economic costs:* Including annual total costs, fuel expenditures, and operational and maintenance expenses.

The fundamental goal of the EnergyPLAN model is to determine the best combination of technologies for constructing an energy system. This is accomplished by examining specified configurations of energy systems in order to improve performance and sustainability. The decision to use EnergyPLAN software is based on its capacity to account for the technical complexities of each technology under evaluation, making it an effective tool for this research. EnergyPLAN strengths in system-wide, hourly simulations, sector integration, and policy-testing; features that are less developed in HOMER, which are microgrid-focused or LEAP, which are long-term, top-down demand-driven.

3.2. Technologies and Economic Parameters

Table 1 presents the forecasted investment cost and lifetime duration of the various technologies used in this research as obtained from the EnergyPLAN database [21]. The table also presents the individual technology's system efficiencies used in this study [22]. 13% interest rate was used, which is the prevailing rate [23]. According to Wood Mackenzie analysis, a 2 % rise in interest rate increases LCOE by approximately 20 %. In this study, a unit installed capacity represents 1 MW.

Table 1. Technologies investment cost, lifetime and O&M percentage cost.

Technologies	Investment (M$/unit)	Lifetime (years)	O&M % of investment	System efficiency (%)
Natural gas PP	0.57	25	3.30	45
Biomass	1.90	40	1.63	45
Wind	0.93	30	3.20	20-40
Photovoltaic	0.71	40	1.28	15-20
Hydropower	5.75	60	1.50	90

3.3. Model Scenarios

To achieve the purpose of this study, a total of 9 case scenarios and a reference model are modeled and simulated to proffer several possible solutions to achieve a set target. Fig. 1 is the flowchart showing the procedural summary of the simulation. The modeled case scenarios are:

Reference Model: 30 GW capacity model of 100% natural gas-fired power plant.
Case 1: 30 GW capacity model, of which 9 GW, that is 30%, will be generated from wind as RES.
Case 2: 30 GW capacity model, of which 30% will be generated from solar PV as RES.
Case 3: 30 GW capacity model, of which 30% will be generated from hydro as RES.
Case 4: 30 GW capacity model, of which 30% will be generated from biomass as RES.
Case 5: 30 GW capacity model, of which 30% will be generated from wind and solar PV as RES.
Case 6: 30 GW capacity model, of which 30% will be generated from solar PV and hydro as RES.
Case 7: 30 GW capacity model, of which 30% will be generated from wind and hydro as RES
Case 8: 30 GW capacity model, of which 30% will be generated from wind, solar PV, and hydro as RES.
Case 9: 30 GW capacity model, of which 30% will be generated from wind, solar PV, hydro, and biomass as RES.

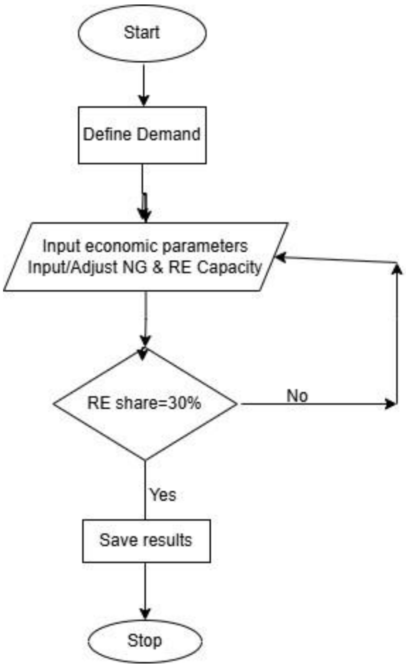

Figure 1. Summary of simulation procedure using EnergyPLAN.

4. RESULTS AND DISCUSSION

This section presents the detailed results of the simulations for the considered case scenarios, the economic implications of meeting the set electricity target, as well as its expected environmental impact.

4.1. Simulation Results

According to the simulation carried out for the reference case scenario, the result shows that a natural gas-fired power plant with 30 GW capacity will produce 170 TWh/yr with a CO_2 emission of 68.04 Mt annually, which will incur a total investment cost and total annual cost of 17.1 billion USD and 2.89 billion USD, respectively. This model serves as a reference model to all other cases in this study with regards to the total electricity generation capacity of 30 GW intended if only fossil fuel (natural gas in this case) is to be used as the source of energy.

Case Scenario 1: With the integration of 21 GW of natural gas-fired power plants and 9 GW of wind (representing 30% of generation capacity) as RES to make a total of 30 GW of installed capacity, a total electricity production of 137 TWh/yr will be achieved. The downside of this system is that total annual electricity production will decrease by about 19.4% in comparison to the reference model. A total of 34.97 TWh/yr of electricity will be generated from wind energy, contributing a 25.5% share as RES from the total electricity to be generated. The system's CO_2 emission will drop by about 40%, from the reference model of 68.04 to 40.84 Mt/yr. This system will incur a total investment cost and total annual cost of 20.34 billion USD and 2.75 billion USD, respectively. The total investment cost increased by 15.9% because the investment cost of wind energy technology is higher than that of natural gas power plants. However, the total annual maintenance cost decreases by about 4.8% because maintaining a wind farm costs less than the NG power plant, as presented also in Table 1. Fig. 2 presents the electricity generation distribution from both NG power plants and wind in comparison to the reference scenario (R-NG).

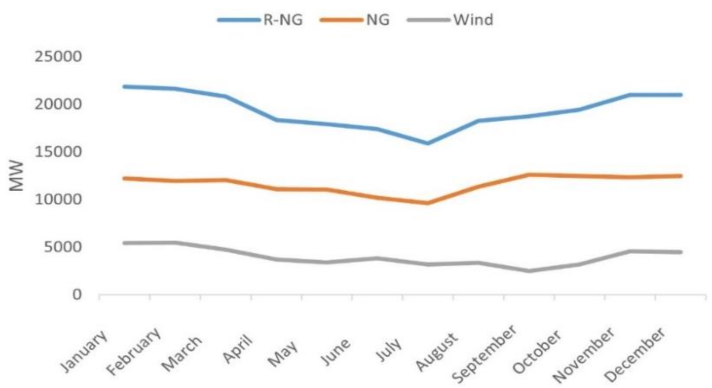

Figure 2. Electricity generation distribution from both natural gas (NG) and wind powerplants.

Case Scenario 2: Integrating 21 GW of natural gas-fired power plant and 9 GW of solar PV as RES to make a sum total of 30 GW of installed capacity, a total electricity production of 119 TWh/yr will be achieved, of which the solar PV plant will generate 22.22 TWh/yr of electricity production, contributing an 18.7% share as RES. The total electricity generation in this scenario is less when compared with case scenario 1, and this is a result of solar PV systems having a lower efficiency than a wind turbine. The system's CO_2 emission will drop down to about 38.74 Mt/yr. The system will incur a total investment cost and total annual cost of 18.36 billion USD and 2.47 billion USD, respectively. The downside of this scenario is that it has the lowest annual total electricity produced, at about 30% less than the reference model, and also the lowest RES share amongst all the considered scenarios. The upside is that it provides the cheapest path to achieving the set target; therefore, if minimizing cost is a top priority, then integrating NG with solar PV is the best option to implement.

Case Scenario 3: In the case of achieving 9 GW capacity from hydro and 21 GW from natural gas power plants, a total electricity generation of 146 TWh/yr will be achieved, of which the hydropower plant will generate 35.37 TWh/yr of electricity, contributing a 26.5% share as RES. The advantage of this scenario is that total electricity generation and percentage RES share are higher than those of both Scenario 1 and 2; this is because the efficiency of a hydropower plant is higher than that of solar PV and wind. The total CO_2 emission will amount to 44.06 Mt/yr and will incur a total investment cost and total annual cost of 63.72 billion USD and 8.36 billion USD, respectively. The downside of this is that implementing this scenario will incur the highest investment cost amongst all the scenarios considered in this study owing to the reason that the cost of installing a hydropower plant per unit is way more expensive than the other technologies, as presented in Table 1.

Case Scenario 4: By integrating 21 GW of natural gas-fired power plant and 9 GW of biomass power plants as RES to make a sum total of 30 GW of installed capacity, a total electricity production of 170 TWh/yr will be achieved, which is the same as that of the reference scenario because the same system efficiency of 45% is considered for both NG-fired power plants and biomass power plants in this study. Biomass will generate 39.27 TWh/yr of electricity production, contributing a 23.1% share as RES. The system's CO_2 emission will drop from 68.06 to 36.39 Mt/yr, and the system will incur a total investment cost and total annual cost of 29.07 billion USD and 3.87 billion USD, respectively, which is about a 41% increase in the investment cost with respect to the reference scenario. The advantage of this case is that it provides the highest amount of total electricity generated amongst all the considered case scenarios; therefore, if the target is to achieve maximum output of electricity generated, then this case offers to be the best option.

Case Scenario 5: Considering two RES of solar PV and wind with capacities of 4.5 GW each and integrating with a 21 GW natural gas power plant, a total electricity production of 132 TWh/yr is achievable, and the system will contribute a 20.1% RES share, of which PV and wind will generate 9.05 TWh and 17.49 TWh, respectively, per year. The system will incur a total investment cost of 19.35 billion USD and a total annual cost of 2.61 billion USD, with a total CO_2 emission of 42.2 Mt. The annual wind and solar PV production is graphically presented in Fig. 3 monthly.

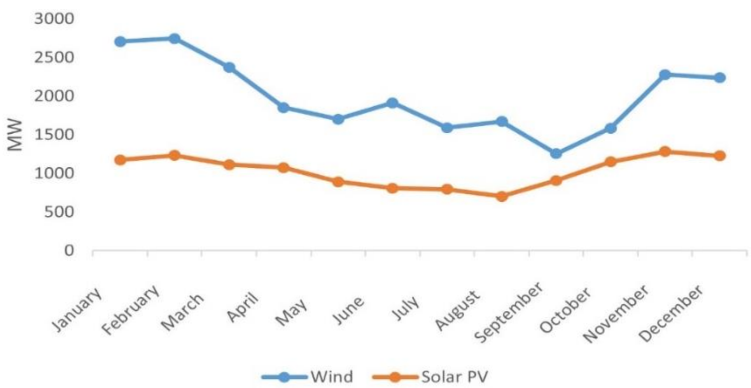

Figure 3. Annual renewable energy production profile of wind and solar PV.

Case Scenario 6: In the case of integrating 21 GW of natural gas-fired power plant and two RES of solar PV and hydropower with capacities of 4.5 GW each to make a sum total of 30 GW installed capacity, a total electricity production of 133 TWh/yr can be achieved, of which solar PV and hydropower will generate 9.05 TWh/yr and 18.53 TWh/yr of electricity, contributing a 20.7% share as RES. The system's CO2 emission will amount to 42.19 Mt/yr and will incur a total investment cost and total annual cost of 41.04 billion USD and 5.42 billion USD, respectively.

Case Scenario 7: In the case of integrating 21 GW of natural gas-fired power plants and two renewable energy resources of wind and hydropower with capacities of 4.5 GW each to make a sum total of the targeted 30 GW installed capacity, total electricity production of 146 TWh/yr can be achieved, of which wind and hydropower will generate 17.49 TWh/yr and 18.53 TWh/yr of electricity, contributing 24.7% RES share. The system's CO2 emission will amount to 44.02 Mt/yr and will incur a total investment cost and total annual cost of 42.03 billion USD and 5.56 billion USD, respectively. This scenario has an advantage over case 5 and case 6 as it produces higher total annual electricity generation when considering two renewable energy sources.

Case Scenario 8: In the case of integrating 21 GW of natural gas-fired power plant and three renewable energy resources of solar PV, wind, and hydropower with capacities of 3 GW each to make a total of a targeted 30 GW installed capacity, total electricity production of 138 TWh/yr can be achieved, of which solar PV, wind, and hydropower will generate 6.03, 11.66, and 12.36 TWh/yr of electricity, respectively, contributing 21.8% RES share. The system's CO2 emission will amount to 43.2 Mt/yr and will incur a total investment cost and total annual cost of 34.14 billion USD and 4.53 billion USD, respectively.

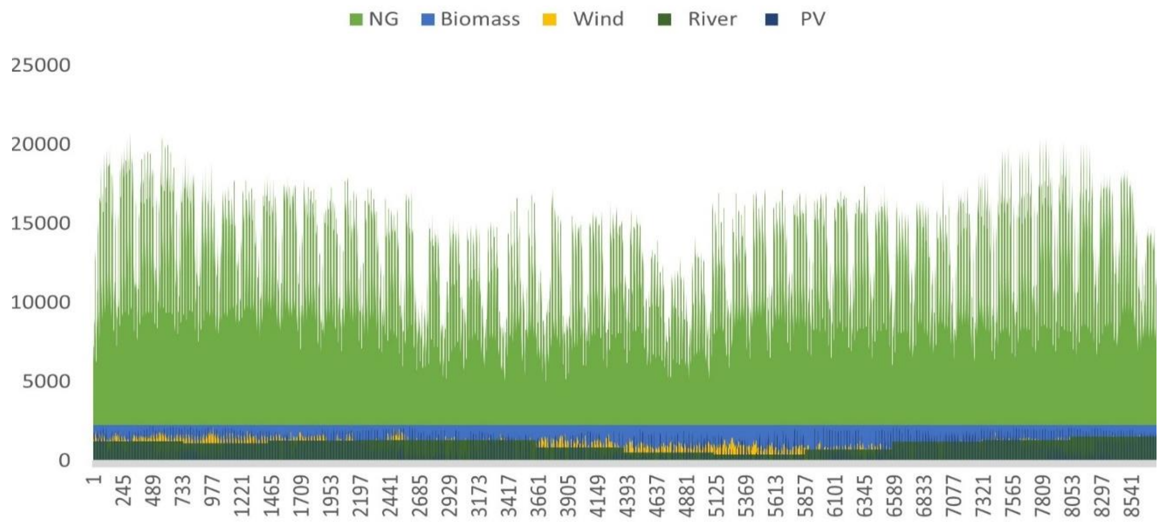

Figure 4. Electricity demand and renewable energy production as annual distribution.

Case Scenario 9: In the case of integrating 21 GW of natural gas-fired power plant and four renewable energy resources of solar PV, wind, hydropower, and biomass with capacities of 2.25 GW each to make a sum total of the targeted 30 GW installed capacity, total electricity production of 147 TWh/yr can be achieved, of which solar PV, wind, hydropower, and biomass will generate 4.52, 8.74, 9.27, and 19.76 TWh/yr of electricity, contributing 26.4% RES share. The system's CO_2 emission will amount to 8.97 Mt/yr and will incur a total investment cost and total annual cost of 32.87 billion USD and 4.36 billion USD, respectively. The annual electricity demand as well as all the annual renewable energy production is graphically shown in Fig. 4. This scenario will generate the 2nd highest total annual electricity generation amongst all the scenarios after the scenario of NG with Biomass. An important advantage is that integrating the four RES provides better stability and security to the grid in the case where one of the sources fails.

Fig. 5 shows the annual electricity generated by all the technologies in all case scenarios. It can be seen that the case of NG with biomass comes first, followed by NG with all four RES considered. The least is NG with solar PV, and this is due to the high intermittency level of solar radiation. Case scenario 4, with biomass generates more electricity because amongst all the renewable energy sources considered, it has the highest (except hydro) and most consistent efficiency of about 45% as presented in Table 1.

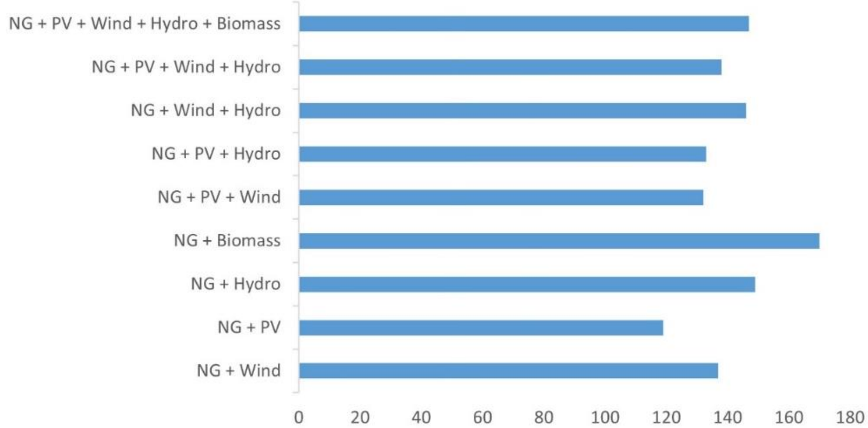

Figure 5. Total annual electricity generated in all case scenarios in TWh/yr.

4.2. Economic Implications

The economy of a nation is directly affected by the level of electricity access and energy stability, as it is one of the pillars supporting manufacturing and productivity as a whole. Table 2 presents a wholesome summary of the financial implications and corresponding renewable energy source percentage share for all the considered case scenarios.

Table 2. Financial implications, capacities and RES share summary.

Technology combination	Capacities (GW)	RES share (%)	Annual carbon emission (Mt)	Total investment (B$)	Total annual cost (B$)
NG (Reference scenario)	30	0.00	68.0	17.1	2.89
NG + Wind	21 + 9	25.5	40.8	20.3	2.75
NG + PV	21 + 9	18.7	38.7	18.4	2.47
NG + Hydro	21 + 9	26.5	43.8	63.7	8.36
NG + Biomass	21 + 9	23.1	36.4	29.1	3.87
NG + PV + Wind	21 + 4.5 + 4.5	20.1	42.2	19.4	2.61
NG + PV + Hydro	21 + 4.5 + 4.5	20.7	42.1	41.0	5.42
NG + Wind + Hydro	21 + 4.5 + 4.5	24.7	44.0	42.0	5.56
NG + PV + Wind + Hydro	21 + 3 + 3 + 3	21.8	43.2	34.1	4.53
NG + PV + Wind + Hydro + Biomass	21+2.25+2.25+2.25+2.25	26.4	8.97	32.9	4.36

For a project targeted for 2030, all the scenarios are financially feasible. An important aspect is putting in place a workable policy for the government. Private sector investment can be considered, or a foreign loan can be obtained to finance the project. Improving the national electricity generation to 30 GW will generally improve productivity in the country, which will eventually result in improved GDP. It is also important to note that integrating renewable energy into the energy mix eventually decreases the cost of electricity, as its operation and maintenance are usually cheaper than that of conventional/fossil fuel energy.

Generally, integrating renewable energy into electricity generation can have a variety of economic repercussions, both positive and negative, depending on factors such as the specific renewable technologies used, the degree of integration, and the local energy market conditions. Some of the positive implications are job creation, improved energy price stability, and revenue diversification for rural communities. According to the International Renewable Energy Agency (IRENA), the renewable energy sector employed around 12 million people worldwide in 2019. Integrating renewable energy into electricity production can thus assist in reducing reliance on imported fossil fuels while mitigating the influence of fuel price volatility on power prices, resulting in greater price stability for consumers and companies.

4.3. Environmental Impact

Mitigating CO_2 emissions, which contribute to global warming, is one of the major reasons for integrating renewable energy sources for electricity generation. This has been an important topic for policymakers, governments, and researchers over the last two decades worldwide. The result of this study shows that case 9, which integrates all the RES considered, has the lowest CO_2 emission of 8.97 Mt, which is about 13.2% of that of the reference scenario (68.04 Mt), followed by case 4, which integrates NG with biomass with CO_2 emissions of 36.4 Mt, as presented in Fig. 6. In essence, integrating renewable energy sources into the energy mix decreases the amount of carbon emissions into the atmosphere by fossil fuels.

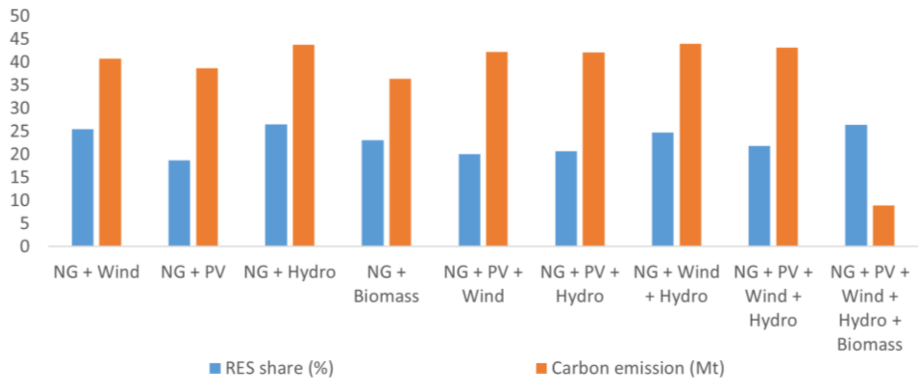

Figure 6. RES percentage share and carbon emission values for all scenarios.

4.4. Risks and Uncertainties

Nigeria's renewable energy regulations have been inconsistently applied, characterized by conflicting mandates and governance issues that may delay or obstruct project approvals and diminish investor confidence; yet, ongoing governmental commitment is crucial for the implementation of suggested scenarios. A critical issue is securing sufficient funding: restricted access to affordable financing, high interest rates, and continuous currency devaluation, coupled with the substantial initial capital requirements of renewable projects, have frequently constrained the deployment of large-scale solar farms and mini-grid efforts. Infrastructure bottlenecks in Nigeria's power system, marked by an antiquated transmission network, persistent underinvestment, recurrent equipment malfunctions, and vandalism, impede the integration and reliable distribution of renewable energy, thereby underscoring the urgent necessity for grid modernization and decentralized energy solutions.

5. CONCLUSION AND POLICY IMPLICATIONS

Nigeria is challenged with low electricity access and difficulty in significantly improving the power generation capacity over the years, despite the rapid increase in its population, which results in a rise in electricity demand; unfortunately, that has played a key role in the slow economic growth of the nation and is also one of the reasons for the high unemployment rate. This study was performed to proffer feasible solutions to meeting the country's electricity generation set target by the year 2030 as well as the impact it will have on economic growth and its environmental implications. To achieve this, the country must set feasible and important policies to be strictly adhered to and committed to.

This study explores the installation of 30 GW of power-generating capacity, of which 30% should be from renewable energy sources, by considering 9 different electricity-generating case scenarios. The result of the various simulations gives several options for the government to opt for with respect to what matters most to the nation, including the maximum annual electricity that can be generated, the option that can generate the highest percentage share of renewable energy, the option with the least carbon emission, and also the option that is the most cost-effective. The key conclusions from the study are:

- *Natural gas-fired power plants with biomass power plants will generate the highest value of electricity, up to 170 TWh, annually.*
- *In terms of RES share, the natural gas-fired power plant with hydropower will produce the highest RES share of 26.5% of the total electricity produced.*
- *The case of integrating a natural gas-fired power plant and four renewable energy resources of solar PV, wind, hydropower, and biomass will produce the least annual carbon emission of 8.97 Mt.*
- *Considering cost-effectiveness, having a natural gas-fired power plant and a solar PV plant will incur the least total investment cost and the annual cost of 18.4 billion dollars and 2.47 billion dollars, respectively.*

It is noteworthy that Case 9 emerges as the most optimal scenario due to its superior environmental performance, characterized by the lowest emissions of 8.97 Mt CO_2 annually. Although its renewable energy share of 26.4% is marginally below the highest observed value, it remains highly competitive. Moreover, this scenario integrates all the renewable technologies considered in the study, thereby enhancing grid stability and energy security relative to the other scenarios with an estimated payback period of 3 years. Also, the scenario best aligns with both the Energy Transition Plan's diversified-RES mandate and the National Renewable Energy and Energy Efficiency Policy of Nigeria.

Considering the Nigeria's current situation and policies, integrating renewable energy into the electricity system necessitates investments in grid infrastructure and upgrading to accommodate fluctuating generation patterns and maintain grid stability. While these initial expenditures may be costly, they can result in long-term benefits such as improved grid stability, higher flexibility, and greater resilience to harsh weather events.

The government can put in place practicable policies and market incentives that can play a crucial role in shaping the economic landscape of renewable energy integration in the country:

- *Providing subsidies on the importation of renewable energy-related materials, equipment, and machinery.*
- *Enhancing and modernizing the grid, along with investing in off-grid solutions, is crucial for broader energy accessibility.*
- *Cooperation between the government and the private sector can expedite project execution and enhance funding alternatives. That is, a public-private partnership approach, with government-backed credit guarantees that would best leverage private capital while mitigating sovereign risk.*
- *Training initiatives aimed at cultivating indigenous proficiency in renewable technology can bolster business expansion and diminish reliance on foreign knowledge.*
- *Educating communities on the advantages of renewable energy can facilitate its adoption and garner support.*

Other policies like tax incentives and implementing a competitive-auction framework for large-scale renewables as obtained in South Africa, renewable energy mandates, introducing feed-in tariffs for small-scale solar/wind to spur rural off-grid investment as obtained in Kenya's renewable energy framework, establishing a dedicated RE grid-upgrade fund, and carbon pricing mechanisms; these are examples of policy instruments that can encourage investment in renewable energy projects and create favorable conditions for market growth.

REFERENCES

[1] Roche MY, Verolme H, Agbaegbu C, Binnington T, Fischedick M, Oladipo EO. Achieving sustainable development goals in Nigeria's power sector: assessment of transition pathways. *Clim Policy. 2019*;*20*(7):846–65. https://doi.org/10.1080/14693062.2019.1661818.

[2] Onisanwa ID, Adaji MO. Electricity consumption and its determinants in Nigeria. J Econ Manag. 2020;41:87–104. https://doi.org/10.22367/jem.2020.41.05.

[3] Saturday NEG. Nigerian power sector: A new structure required for effective and adequate power generation, transmission and distribution. *Glob J Eng Technol Adv. 2021*;*7*(1):6–18. https://doi.org/10.30574/gjeta.2021.7.1.0035.

[4] Aguda OO. Constitutional and institutional governance of electricity sector in Nigeria. J *Energy Res Rev. 2023*;*14*(4):32–44. https://doi.org/10.9734/jenrr/2023/v14i4291.

[5] Ibrahim ID, Hamam Y, Alayli Y, Jamiru T, Sadiku ER, Kupolati WK, et al. A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. *Energy Strateg Rev. 2021*;*38*:100740. https://doi.org/10.1016/j.esr.2021.100740.

[6] Jacal S, Straubinger FB, Benjamin EO, Buchenrieder G. Economic costs and environmental impacts of fossil fuel dependency in sub-Saharan Africa: A Nigerian dilemma. *Energy Sustain Dev. 2022*;*70*:45–53. https://doi.org/10.1016/j.esd.2022.07.007.

[7] Centre for Petroleum, Energy Economics and Law (CPEEL). *Renewables to drive FG's target of 30 GW on-grid power capacity by 2030* [Internet]. [cited 2024 December 1]. Available from: https://cpeel.ui.edu.ng/news/renewables-drive-fgs-target-30-gw-grid-power-capacity-2030.

[8] Onyegbula E. FG reiterates commitment to renewable energy target in 2030 [Internet]. *Vanguard Nigeria; 2022 Jul* [cited 2025 May 12]. Available from: https://www.vanguardngr.com/2022/07/fg-reiterates-commitment-to-renewable-energy-target-in-2030/.

[9] Duan H, Mo J, Fan Y, Wang S. Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. *Energy Econ. 2017*;*70*:45–60. https://doi.org/10.1016/j.eneco.2017.12.022.

[10] Cui L, Li R, Song M, Zhu L. Can China achieve its 2030 energy development targets by fulfilling carbon intensity reduction commitments? *Energy Econ. 2019*;*83*:61–73. https://doi.org/10.1016/j.eneco.2019.06.016.

[11] Coppens L, Gargiulo M, Orsini M, Arnould N. Achieving −55% GHG emissions in 2030 in Wallonia, Belgium: Insights from the TIMES-Wal energy system model. *Energy Policy. 2022*;*164*:112871. https://doi.org/10.1016/j.enpol.2022.112871.

[12] Government of Belgium. Belgium's long-term strategy [Internet]. [cited 2024 December 1]. Available from: https://unfccc.int/sites/default/files/resource/LTS_BE_EN_summary.pdf.

[13] European Commission. Belgium's draft update of the Belgian National Energy and Climate Plan [Internet]. [cited 2024 December 1]. Available from: https://commission.europa.eu/document/download/73fd2378-8c49-4840-b0cb-22a5548ee541_en.

[14] Samargandi N, Islam MM, Sohag K. Towards realizing vision 2030: Input demand for renewable energy production in Saudi Arabia. *Gondwana Res. 2024*;*127*:47–64. https://doi.org/10.1016/j.gr.2023.05.019.

[15] Acar S, Kat B, Rogner M, Saygin D, Taranto Y, Yeldan AE. Transforming Türkiye's power system: An assessment of economic, social, and external impacts of an energy transition by 2030. *Cleaner Energy Syst. 2023*;*4*:100064. https://doi.org/10.1016/j.cles.2023.100064.

[16] Erat S, Telli A, Ozkendir OM, Demir B. Turkey's energy transition from fossil-based to renewable up to 2030: milestones, challenges and opportunities. *Clean Technol Environ Policy. 2020*;*23*(2):401–12. https://doi.org/10.1007/s10098-020-01949-1.

[17] Gómez-Calvet R, Martínez-Duart JM, Gómez-Calvet AR. The 2030 power sector transition in Spain: Too little storage for so many planned solar photovoltaics? *Renew Sustain Energy Rev. 2022*;*174*:113094. https://doi.org/10.1016/j.rser.2022.113094.

[18] MITERD (Ministry for the Ecological Transition and the Demographic Challenge). National Climate and Energy Plan (NECP) 2019 [Internet]. [cited 2024 December 1]. Available from: https://energy.ec.europa.eu/system/files/2020-03/el_final_necp_main_en_0.pdf.

[19] Bamisile O, Huang Q, Xu X, Hu W, Liu W, Liu Z, et al. An approach for sustainable energy planning towards 100% electrification of Nigeria by 2030. *Energy*. *2020*;*197*:117172. https://doi.org/10.1016/j.energy.2020.117172.

[20] Adewuyi OB, Kiptoo MK, Afolayan AF, Amara T, Alawode OI, Senjyu T. Challenges and prospects of Nigeria's sustainable energy transition with lessons from other countries' experiences. *Energy Rep. 2020*;*6*:993–1009. https://doi.org/10.1016/j.egyr.2020.04.022.

[21] Aalborg University. EnergyPLAN Cost Database [Internet]. [cited 2024 December 1]. Available from: https://www.energyplan.eu/useful_resources/costdatabase/.

[22] International Energy Agency (IEA). IEA Reports [Internet]. [cited 2024 December 1]. Available from: https://www.iea.org/reports/.

[23] Adun H, Ishaku HP, Jazayeri M, Dagbasi M, Olusola B, Okoye T, et al. Decarbonization of EU energy sector: techno-feasibility analysis of 100% renewables by 2050 in Cyprus. Clean *Technol Environ Policy*. *2022*;*24*(9):2801–24. https://doi.org/10.1007/s10098-022-02356-4.