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# Systematic Strategies for Decarbonizing Nigerian Energy and Transport Sectors

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**ABSTRACT**

**The Nigerian energy and transport sectors heavily relied on fossil fuels, and electricity to thrive in modern economy. Thus, it has elevated the levels of energy poverty and emissions, and the untapped potential of renewable energy sources. The alarming consequences of climate change is another factor that have fueled a global movement to transition of cleaner energy sources. Remarkably, Nigeria has actively embraced this movement, demonstrating its commitment through unwavering participation in the Paris Agreement. This study seeks to develop energy plan model that serves as an input/output simulation tool designed for energy system analysis. The proposed model is specifically tailored towards a high renewable energy system. Also, a strategic energy planning, and economic analyses that emphasizes the integration of renewable energy to achieve low carbon energy penetration was developed. The model was validated by comparing the energy plan simulations with actual data from Nigeria's energy system in 2020. Results show the environmental and economic benefits of increasing renewable energy percentages in the energy mix. The techno-economic analysis focuses on Wind, River Hydro, and Solar technologies for 2050. Simulations reveal the linear relationship between renewable energy supply and reduced CO2 emissions and total annual costs. The study suggests scaling up Hydroelectricity, followed by Solar and Wind energy, based on economic considerations, water availability, and technology reliability.**

## 1. INTRODUCTION

Despite the ongoing global energy transition from fossil fuels to renewable energy, the Nigerian energy and transport sectors have heavily relied on fossil fuels, and electricity to thrive in modern economy. Thus, it has elevated the levels of energy poverty and emissions, and the untapped potential of renewable energy sources. The alarming consequences of climate change is another factor that have fueled a global movement to transition of cleaner energy sources. Remarkably, Nigeria has actively embraced this movement, demonstrating its commitment through unwavering participation in the Paris Agreement. The effect of non-renewable energy consumption has facilitated the production of carbon emission. Thus, leading to a vicious circle in policy priority between pollution reduction and economic growth. The pursuit for sustainable environment and stable economic is becoming a contemporary issue among international institutions, governments, and other interested stakeholders. Thus, there is a need to develop energy plan that will increase finance of programs that mitigate global warming.

A crucial aspect of the energy challenges lie in the need to decarbonize the energy and transport sectors, which are major contributors to greenhouse gas emissions. However, Ullah *et al.*(2021) observed a significant increase in the worldwide need for

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energy due to rapid population growth and industrial growth. Das *et al.* (2019) suggested that this trend presents a grave risk to economies, energy security, and the pursuit of sustainable development. Aprillia and Rigoursyah (2020) emphasised on the benefit of solar energy remains enormous even when compared to other forms of renewable energy forms such as the wind turbine, though a renewable energy source; however, it normally have the associated problem of noise during operation, requiring open and spacious areas for installation while photovoltaic cell can easily be mounted on rooftops.

This study places high emphasis on replacing the present fossil fuel-based energy and transport system with biofuels, electric vehicles, solar, wind and hydro to provide cleaner energy systems with its overwhelming benefits.

## 2. LITERATURE REVIEW

As the world transitions to a more sustainable energy for the future, it becomes imperative to harness clean and renewable energy. Hence, renewable energy has emerged as a pivotal player in the quest for a low-carbon future. Nigeria, as a rapidly growing economy, and the most populous country in Africa, faces significant challenges in addressing the climate change, and achieving sustainable development.

There are several literature on EnergyPlan, transportation and energy consumption. Raghuwanshi and Arya (2020) studied the demerits of hydroelectricity requires construction of dams, which are expensive and building dams affects aquatic life, and has the potential of altering an entire ecosystem. Kabir, *et al.,* (2018) studied the difference between Concentrated Solar thermal for heating requirements, and concentrated Solar power for generating electricity combining with high-magnification mirrors to prior concentrate solar energy to convert it into heat energy to power a steam turbine.

Dagoumas and Koltsaklis (2019) emphasis the variety of computer tools for modelling and assessing energy systems at both national and regional scales to facilitate the development of transition strategies. Ringkjøb et al. (2018) outline the three main methodological approaches utilized in energy system modeling, which include optimization, simulation, and equilibrium tools or models. Optimization tools concentrate on internally optimizing system design, simulation tools replicate externally defined energy systems, while equilibrium tools involve broader econometric models of society. Priesmann *et al.* (2019) found in their systematic analysis of power system optimization models that increased model complexity does not necessarily guarantee higher accuracy. Similarly, Pilpola and Lund (2020) highlighted the significant impact of uncertainties and input variations on the performance of simulation models for low-carbon energy systems. Maduekwe *et al.* (2020), Shabbir and Ahmad (2010), Emodi *et al.* (2017), Dioha and Kumar (2020), Vaillancourt *et al.* (2008), Limanond *et al.* (2011), Murat and Ceylan (2006), and Polemis (2006) discuss various techniques and methodologies for analysing and forecasting energy demand and GHG emissions. These include models such as the LEAP model, TIMES model, artificial neural network, and econometric approaches. However, many of these methodologies necessitate extensive input data. For instance, the LEAP model heavily relies on demographic and macroeconomic data, which might not be readily accessible in Nigeria.

However, selecting the right tool for devising future energy system scenarios, particularly concerning Nigeria, presents a significant challenge. Nonetheless, based on a review of thirty-seven computerized tools for analysing renewable energy integration into diverse energy systems , the EnergyPLAN model was selected for this study. There exists an abundance of literary works on the application of this software. The simulator has been instrumental in offering critical insights and capacity for zero carbon energy ecosystems (Abdulganiyu, 2017), developing comprehensive energy system models (Ma *et al.*, 2014), investigating the need of energy storage in RES systems. (Lund and Mathiesen, 2009), and predicting the optimization of different fluctuating RES in the electricity system (Lund, 2006). Additionally, the tool has been effectively utilized to simulate energy systems with a high share of renewable energy across several countries, including Latvia, the United Kingdom, Macedonia, Denmark, Kenya, and Tanzania.

Study on Nigeria's transportation sector spans energy utilization, GHG emissions, and vehicle ownership determinants. Badmus *et al.* (2012) utilized exergy methods to analyse energy consumption trends in transportation from 1980 to 2010, revealing an average energy efficiency of 17.11% and exergy efficiency of 15.97%. They noted adverse effects of importing used vehicles on the road sector's performance. *Maduekwe et al. (2020)* employed the LEAP model to project energy consumption and GHG emissions in Lagos State, proposing measures for a 50% reduction in emission by 2032 through limiting vehicle age and ownership growth. Abam *et al*. (2021) conducted decomposition analysis from 1988 to 2019, estimating a significant 163% increase in carbon emissions from the transportation sector, reaching 44.45 million tonnes of $CO_2$. Dioha and Kumar (2020) explored alternative policy pathways using the TIMES model for 2010-2050, foreseeing substantial CO2 emission reductions. Gujba *et al.* (2013) based on life cycle assessment and economic consideration advocated for the promotion of public bus usage as a more sustainable option.

On vehicle ownership, Ukonze *et al.* (2020) identified per capita income, GDP, price of fuel , education level, and public transport availability as key determinants. Kolli *et al*. (2010) highlighted the role of vehicle mileage economy in vehicle longevity, while Hamilton and Macauley (1999) emphasized user travel attitudes. Choo and Mokhtarian (2004) suggested that vehicle choice is influenced by personal attitudes. However, research gaps exist in understanding the lifespan distribution and survival rates of vehicles in Nigeria.

## 3. MATERIALS AND METHODS

Nigeria is roughly located within longitudes 3° and 15° east of the Greenwich meridian and latitudes 4° and 14° north of the equator, Nigeria is the most populated in Africa with approximately 923,768km2. Vitalis and Oruonye (2021) projected that the population of Nigeria by 2025 to be 239 million and 440 million by 2050. This positions Nigeria as the fourteenth largest country by land mass in Africa and ranks Nigeria as the 4th most populous country World. Figure 1 shows the geographical map of Nigeria.


**Figure 1:** Geographical map of Nigeria

Data source: United states Central Intelligence Agency, CIA World Factbook-Nigeria

As the population grows, the need for more energy to power industries, for cooking, to provide electricity for homes, to fuel vehicles for transport (land, air and sea) as well as Provision of commercial venture becomes essential. NBS and SMEDAN (2010) stated the demand for electricity in Nigeria is currently increasing more above the supply from the national grid. A significant proportion of this shortfall is met with onsite generating sets at various consumer locations; some of these power generators, operates between 15-18 hours a day. Regrettably, these diesel generators releases fine particles of matter , including black carbon, originating from the inproper combustion of automotive motor oil(diesel), a common occurrence in many diesel generator sets.

Currently, shortage of electricity has been a widespread experience in Nigeria. Insufficient generation can result into frequent power outage conditions and rationing of energy supply. Insufficient access to energy can lead to a strain on livelihood of people. This issue does not primarily stem from an absence of energy resources, but rather can be ascribed to factors such as inadequate resource planning and management, ineffective energy policies, economic difficulties, and limitations in funding and executing energy initiatives.

The occurrence of unstable power supply and frequent power outages is a common issue in Nigeria. For instance, Nigeria as a country faced a complete grid collapse severally every year. To fulfil their energy requirements, there is a growing focus on using backup generators for self-generation. However, relying on these backup generators consistently comes with significant financial burdens for the local population. The exponential rise in demand for electricity and persistent grid failures necessitate the exploration of alternative power sources. Marocco, *et al.,* (2021) posits that sustainable energy sources are expected to play a pivotal role in guaranteeing a clean environment and sustainable development.

Ashurst. (2022) did a study and found out that Nigeria currently is among the comity of nations of the world with the highest energy poverty index. One third of the families in Nigeria have no access to electricity. He also found out that waste and biomass are the major source of energy for cooking in rural areas. Ashurst. (2022) discovered that, Nigeria's electricity expenses rank among the highest globally, averaging around US$0.52 per kilowatt-hour. This is as a result of the skyrocketing price of diesel generators as well diesel. With an average of 20 to 30 million functional diesel generators in the Nigeria, the generating capacity from diesel generator in Nigeria is estimated to be between 25000MW to 60000MW .Because Nigeria's oil refineries are in a state of disrepair, the country must import diesel, which increases the expense of generating electricity. Both industrial and residential consumers depend on diesel powered generators for their energy need because of the insufficient condition of the nation's electricity infrastructure.

EnergyPLAN model as a sophisticated simulation tool designed to analyse energy systems comprehensively. It operates on an input/output basis, simulating the behaviour of energy systems on an hourly basis over the course of a year. This model is specifically tailored for energy planning purposes, focusing on both technical and economic aspects. It places particular emphasis on accommodating high levels of renewable energy, which are essential for achieving a significant presence of low carbon energy sources in the overall energy mix. In Figure 2, outlines the layout of the EnergyPlan simulation tool.

The EnergyPLAN model's goal is to highlight the best technology mix for configuring the energy system. This is achieved by evaluating pre-defined energy system configurations. EnergyPLAN software was used based on the fact it considers all the technical specifics of each of the technologies investigated in this study. Each of the technologies considered in this study was first simulated to meet the total demand; afterward, two or more technologies were combined for electricity generation. It is noteworthy that EnergyPLAN only utilizes the use of pump hydro-storage with RE

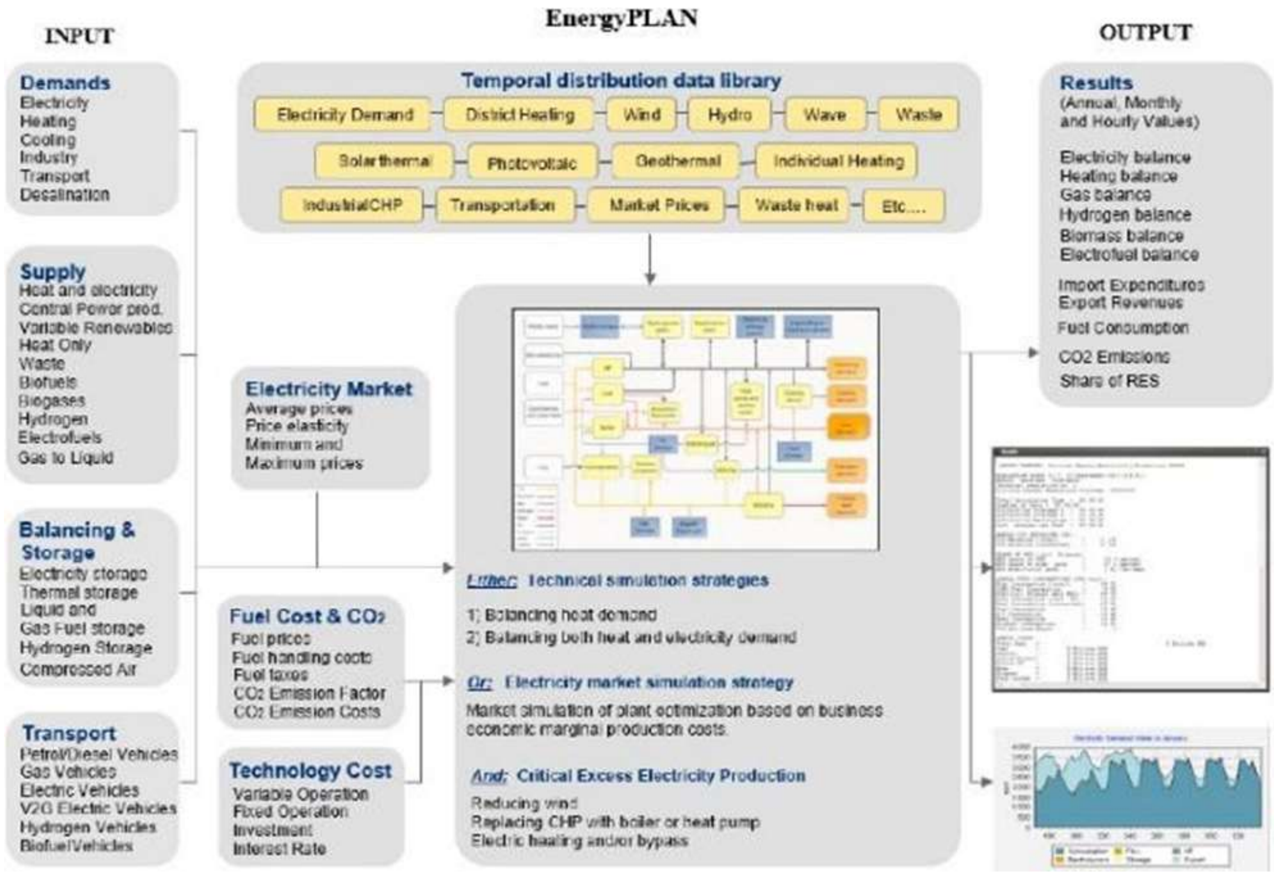


Figure 2 Layout of EnergyPLAN

power plants. The model used in estimating the required generation capacities and the procedure for optimization to abate the energy poverty in Nigeria, with priority given to RES, of which the main aim is to integrate as much share as possible. After each simulation run , based on the defined supply, there are five possibilities such as

a. No CEEP and PPI warning: this indicates that the defined supply is sufficient for the set demand.
b. 2.CEEP and PPI warning: this indicates that the power produced is not enough to meet the demand. However, there is excess production by some of the RES at some point.
c. 3.CEEP warning: indicates there's excess production by some of the RES at some point; therefore, RES supply capacity should be reduced.
d. 4.PPI warning this indicates that the power produced is not enough to meet the hourly demand. Supply is increased with priority given to RES.
e. 5.The design of the tool is constructed to avoid power production import (PPI). Moreover, CEEP is reduced in the simulation process.

### *3.1 Energy System Scenario Design and Development*

In this study, non-renewable and RES technologies were considered to meet total demand. For non-renewable, natural gas power generation technology was considered, and for RES technologies, river hydro, solar PV and onshore wind power systems were considered due to the potential high-level

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availability in Nigeria. Moreover, due to the intermittency of these renewable sources, pumped hydro storage is the only type of storage facility considered in this study. The natural gas-fired power plant was the only non-renewable technology considered in this research; one of the reasons being that it abundantly available in Nigeria. Hydropower is the major renewable source currently in use in Nigeria. Hydropower is more expensive than the other RES technology considered in this research in terms of investment cost, but it is the most reliable and with the highest capacity factor among them. Solar PV technology is the cheapest in terms of both investment cost and operation and maintenance.

Wind energy technology is considered due to its relatively high potential in the northern Nigeria. It is also relatively cheap compared to hydropower.

Pumped Hydro storage system is the most sustainable and environmentally friendly storage method, hence its choice in this research. A BAU model of Nigeria's energy system for the year 2020 was created, this is due to it being the most recent year for which Nigeria has complete energy data available. The input data were based on IEA energy projections for Nigeria (IEA, 2021). The 2030 scenario is based on projections from IEA.

Finally, the model for the 2050 Renewable scenario has been developed. This scenario aims to boost the percentage contribution of renewable energy to electricity supply by over 80%. Additionally, energy demand for other sectors was forecasted based on IEA energy demand projections. However, the scenario undergoes several iterations to decrease fossil fuel usage by about 50% in the transportation sector. This reduction is replaced by the adoption of electric vehicles, fuel cells, and biofuels.

### *3.2 Basıc Assumptıons For The Desıgn*

The following are the principal assumptions underlying the design of Nigeria's future energy landscape:

a) Construction of new biomass plants is assumed, while the use of coal as an energy source is phased out.

b) Growth in the transport sector is projected to align with the National Energy Master Plan's 7% growth scenario. The assumption is that the number of vehicles per 1000 people will increase from 60 in 2018 (based on data from the National Bureau of Statistics/Federal Road Safety Corps, 2018) to 200 by 2050, with approximately 2 million of these vehicles being electrically powered.

c) Biofuel is anticipated to constitute 20% of the fuel mix in the transport sector, based on preliminary studies from various sources (NNPC, 2007; Abila, 2010; Agba, et al., 2010; Ohimain, 2013).

d) Introduction of fuel cell vehicles into Nigeria's transport mix is expected by 2030.

e) It is assumed that there will be continuous operation of the power plants throughout the year, with no interruptions in the power networks.

f) The constraints related to inadequate distribution and transmission lines for electricity generation are disregarded.

A thorough evaluation was conducted by comparing the EnergyPLAN reference model with the real data from Nigeria's energy system in 2020, sourced from the International Energy Agency (IEA, 2021). This step is crucial to verify the capability of EnergyPLAN in producing precise simulation results. The validation methodology applied aligns with the procedures employed by Ma et al. (2014) and Abdulganiyu (2017). After that different scenarios were developed as explained.

*3.3 Business-as-usual (BAU) Scenario*

In the business-as-usual scenario, it is assumed that electricity consumption per capita remains constant through 2030 and 2050. The electricity demand is derived from population projection data provided by the United Nations, Department of Economic and Social Affairs, Population Division (2020), as illustrated in Tables 1., 2 and 3.

**Table 1:** Projected Population and Electricity demand for Nigeria.

| Year | 2020 | 2030 | 2050 |
|---|---|---|---|
| Population(Millions)* | 206 | 264,068 | 410.638 |
| Electricity Demand(TWh) | 34.33** | 131.5*** | 410.64 |

Source: * United Nations, DESA, Population Division (2017)

** IRENA, 2022

*** Calculations based on

* power demand estimates from literature

**Table 2:** Electricity supply in BAU scenario

| Generation in 2020 | GWh | Mwe | % |
|---|---|---|---|
| Non-Renewable | 27042 | 3086.986301 | 76.88 |
| Renewable | 8280 | | 23 |
| Hydro | 8226 | 939.0410959 | 23 |
| Solar | 42 | 4.794520548 | 0.12 |
| Wind | 0 | | 0 |
| Bio-Energy | 21 | 2.397260274 | 0 |
| Geothermal | 0 | | 0 |
| Total | 35331 | 4033.219178 | 100 |

Source: IRENA 2020

This scenario expects no departure from the present trajectory concerning energy demand, vehicle technology, and fuel standards in the transportation sector. Amulah et al. (2023) offer forecasts for fuel consumption in both 2030 and 2050. The data are presented in Table 4

**Table 3:** Electricity Consumption in Nigeria by sector

| | Industry | Residential | Commercial and public services | Total Energy Consumption(TJ) | Total(Twh) |
|---|---|---|---|---|---|
| 1990 | 7258 | 14216 | 6862 | 28336 | 7.849072 |
| 1995 | 7333 | 17820 | 8816 | 33969 | 9.409413 |
| 2000 | 6718 | 15952 | 8446 | 31116 | 8.619132 |
| 2005 | 7628 | 37087 | 17114 | 61829 | 17.12663 |
| 2010 | 11696 | 43063 | 19616 | 74375 | 20.60188 |
| 2015 | 14393 | 51764 | 23994 | 90151 | 24.97183 |
| 2020 | 13747 | 58910 | 27304 | 99961 | 27.6892 |

Source: IEA (2022) World Energy Balances https://www.iea.org/data-and-statistics/data-product/world-energy-statistics-and-balances

**Table 4:** Road transport energy consumption in BAU scenario

| Year | Petrol (ktoe) | Diesel (ktoe) | Petrol(Twh) | Diesel (Twh) |
|---|---|---|---|---|
| 2020 | 12823 | 3314 | 149.1315 | 38.54182 |
| 2030 | 19856.09 | 4710.223 | 230.9263 | 54.77989 |
| 2050 | 30097.49 | 6550.961 | 350.0338 | 76.18768 |
| 1Ktoe | 0.01163 | 1 Twh | | |

*3.4 Energy for the Future In Nigeria*

This scenario aligns with the Nigeria Renewable Energy Master Plan (ECN, 2005) for the year 2030, which anticipates a 36% increase in the contribution of renewable energy to electricity generation in Nigeria. For the year 2050, the electricity supply was planned to ensure that the percentage contribution of renewable energy to electricity supply exceeds 70%.In the transport sector, it is assumed that biofuel is used to substitute fossil fuel. The reference year conditions are similar with the BAU scenario and by 2030 and 2050 all fossil fuels are replaced with biofuel. The specifications for this scenario are shown in Table 5

Table 5: Specification for the biofuel scenario

| Fuel Type | Capacity (MW) | |
|---|---|---|
| | 2030 | 2050 |
| Coal | 10984 | |
| Natural gas | 80560 | |
| Solar | 25917 | 70000 |
| Hydro | 6533 | 17759.4 |
| Wind | 29 | 25000 |
| Biomass | 54 | |
| Nuclear | 3500 | |
| Transport sector | 24566.31* | 36648.45* |
| Coal | 10984 | |

*Unit: ktoe

The Battery Electric Vehicle is gradually being introduced to substitute petrol vehicles for passengers and replace diesel-powered trucks and buses by 50%, 70%, and 90% in 2030 and 2050 respectively.To make this conversion, it is assumed that electric vehicles have an efficiency of 0.62 MJ/km (6km/kWh). For example, Tesla-Model X Standard Range has a specific fuel 19.2 kWh/100km, while diesel and petrol vehicles have average efficiencies of 1.4 up to 1.5(MJ/km) and 1.8 up to 1.9(MJ/km), respectively. The operating strategies of the reference system are modelled, simulated, and adjusted using EnergyPLAN modelling tool until the outputs correspond to that declared from official energy reports. Nigeria's biggest energy imports are fossil fuels fueling the transportation sector's energy demand, hence new alternatives and smart renewable energy strategies are proposed.

### *3.5 Techno-Economic Analysis of Different Renewable sources of energy for Nigeria in 2050*

The methodology is to compute and compare different renewable alternatives and determine which renewable energy source is preferred based on Economics and Environment sustainability. The Simulations was carried out with different Renewable sources of energy such as wind, River Hydro and Solar.

The EnergyPLAN simulator was set to run on series mode where Energy input are iterated and ran against different outputs. The input of energy was iterated from 1000 MW to 11000MW of energy supplied for solar and wind energy while the outputs were CO2 emitted and Total Annual cost. The input energy for River hydro was iterated from 2000MW to 22000MW, the outputs were Co2 Emitted and Total Annual Cost.

The attendant consequences of utilizing fossils for Energy need leads to emission of Green House gases which lead to climate change. Climate change effects include flooding, respiratory ailments, environmental degradation amongst others. UN. (2015).At the UN Climate Change Conference (COP21) in Paris, France, on 12 December 2015,196 countries of the world including Nigeria committed to Its overarching goal which is to hold "the rise in the global average temperature to below 2°C " and intensify efforts "to maintain the temperature rise to 1.5°C above the levels before the industrial revolution." In order to meet up the Paris Agreement as well as provide sustainable energy to meet up with Nigeria future Energy Mix, gradual replacement of Fossil fuel powered energy systems with Sustainable Energy technologies like Wind Energy, Solar Energy, Energy Storage, Electric Vehicles, Hydropower, Smart Grids, Biofuels, Fuel Cells.

However, the actual socio-economic impacts of the Sustainable energy sources vary significantly by the cadre of technological development of the different countries. Thus, local feasibility assessments of new energy sources for the transportation sector are essential, to drive the environmental sustainability agenda of the UN.

Ashurst (2022) according to their research, discovered that Nigeria emits remarkably low volumes of carbon emissions per capita, amounting to 0.61 metric tons of CO2 equivalent per capita in 2020. This stands in stark contrast to figures of 14.24 metric tons of CO2 equivalent per capita in united states of America and 4.85 metric tons of CO2 equivalent per capita in the United Kingdom. Despite this, Nigeria ranks 17th as Nations that emit greenhouse gases worldwide. This is primarily attributed to emissions of CO2 and methane resulting from gas flaring and venting during petroleum and natural gas production. The computation operates as illustrated in the following scenario: 1.9 million cars, each linked to the grid at 10 kW, with an annual demand of 2 MWh, equivalent to driving 20,000 km per year.The charger and inverter efficiencies are each defined as 0.9. In total, the demand for transport becomes DV2G=3.8 TWh/year and a maximum capacity of 19,000 MW. The efficiencies of both the charger and inverter are set at 0.9. Consequently, the total transport demand amounts to DV2G=3.8 TWh/year with a maximum capacity of 19,000 MW.

IEA (2019) reported that the Nigeria’s transportation sector also faces a lot of challenges. Approximately 13% of the overall final energy consumption and around 92% of the total final oil product consumption are attributed to this industry. Badmus, et al(2012) found out that among various transportation modes, road transport predominates in Nigeria, constituting approximately 98% of the total fossil fuel consumption within the transportation sector.

Dioha and Kumar(2020) anticipated factors such as population growth, urbanization, rising household incomes, and the subsequent surge in both vehicle numbers and people movement are anticipated to add to a significant escalation in energy demand within this sector.

Nigeria's road transport system faces dual challenges, encompassing inadequate infrastructure and suboptimal vehicle conditions along with poor fuel quality. According to the ADB (2013), only approximately 27% of the federal road network is in good condition, while 30% is deemed fair, and a significant 40% is unfit for use. Similar conditions can be observed in state and local government roads. Ezenwa(1986), Adepoju, (2021) and Oroleye(2019) posits that the infrastructural issues stem from design specifications falling below required standards insufficient maintenance, discontinuity of projects across successive governments and a lack of equipment and funding for maintenance agencies.

The state of vehicles on the roads presents a substantial challenge. Maduekwe, *et al.* (2020) estimated that 90% of vehicles imported into the country have previously been in use elsewhere, remaining operational for nearly forty years. Miller (2019). emphasised that fossil fuels and products utilized in Nigerian vehicles exceed European sulphur level standards by approximately 100 times. This high sulphur content complicates the enforcement of vehicle emission standards. Despite the Ministry of Transport’s attempts to prohibit the importation of 15 years old used vehicles and above, enforcement faces challenges due to porous borders, smuggling, and corruption. The compromised state of the road transport sector makes it a main contributor to greenhouse gas (GHG) emissions and the consequent ambient air pollution.

Dioha and Kumar. (2020). They suggested five different policy options for enhancing the Nigerian transportation sector. These options include fuel switching, enhancing fuel efficiency, shifting transportation modes, improving logistics, and implementing a carbon tax beginning from 2010 to present day and into the future.They found out that alternative pathways will reduce energy demand ,reduce CO2 emission ,enhance air quality, Improve energy security and as well optimize the productive use of energy. They also found out that introduction of carbon tax and introduction of vehicles that are designed with optimized fuel economy can lower Nigeria's CO2 emissions to 26.9% by 2050 as compared to 42.8% in the business as usual scenario.

## 4. RESULTS

The Analysis and results of the study were presented in this section. A comparison between the Business as Usual (BAU) model created in EnergyPLAN and the actual data from Nigeria's energy system in 2020, obtained from IEA (2021), was undertaken to ensure the accuracy of EnergyPlan's results. This study adopted the validation procedure utilized by Ma et al. (2014) and Abdulganiyu (2017). The scenarios were assessed based on their greenhouse gas emissions in $CO_2$ eq and their associated costs.

A simulations were carried out for Nigeria energy systems maintaining the business-as-usual scenarios in the future (2030 and 2050) as shown in Figure 2.

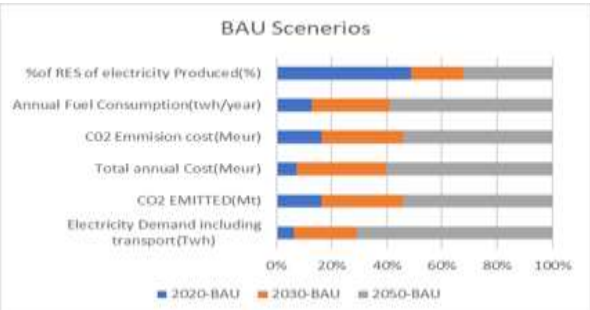


**Figure 2:** Nigeria Business-as-usual scenarios

Findings from the Figure 1 shows a total annual cost and $CO_2$ emission costs increase substantially in the 2030 and 2050 scenarios in comparison to 2020 BAU based on projected economic growth and population increase in Nigeria, highlighting potential economic challenges associated with business-as-usual growth. $CO_2$ emissions rose significantly over the scenarios, and the percentage of RES remains relatively low. This indicates that attaining environmental sustainability goals will be challenging without substantial alterations to energy production and consumption patterns.

Table 6 shows the comparison by EnergyPLAN and actual data in 2020. Table 1 shows the energyPLAN and the actual data.

**Table 6:** Comparison of Electricity Generation by EnergyPLAN and Actual data I 2020(TWh)

| Production Mode | Electricity Production | | Difference |
|---|---|---|---|
| | Actual(2020) Twh | EnergyPLAN(2020) TWh | TWh |
| Hydropower | 8.26 | 8.26 | 0 |
| Gas Power | 27 | 27.08 | 0.08 |
| Solar Power | 0.02 | 0.02 | 0.02 |
| Bio Energy | 0.02 | 0.02 | 0 |
| Import | 0 | 1.02 | -1.02 |
| Total Production | 35.32 | 35.36 | -0.04 |

In Table 2, the energy mix of Nigeria for 2022 has stated by IRENA(2020) is 23% for RES and 77% Non -renewable energy source. This validated the accuracy of the EnergyPLAN software which produced the same results. The scenarios indicate a need for strategic interventions to address both economic and environmental concerns. Transitioning to cleaner energy sources and improving energy efficiency could be essential for achieving long-term sustainability goals while managing economic costs.

Energy for the future in Nigeria using RES scenarios was presented in Figures 2 and 3. Augmenting the proportion of renewable energy sources while maintaining the same energy demand will result in decreases in

Total Annual Cost, total fuel consumption, $CO2$ emissions, and the subsequent cost associated with $CO2$ emissions.

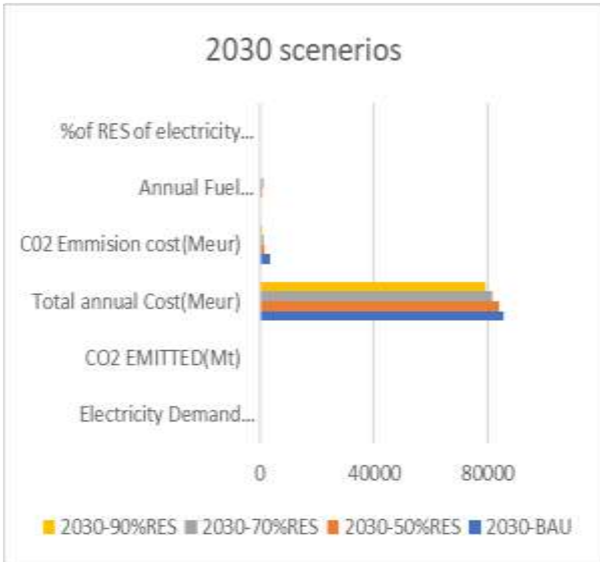


**Figure 3:** Energy for the Future in Nigeria Using RES 2030 Scenarios

The trend in Figures 2 and 3 suggested that to have a sustainable energy future for Nigeria, the percentage of RES need to be increased. This is a similar trend from 2030 where by increasing the percentage of RES, the Total annual cost, Annual Fuel Consumption, $CO_2$ emission and $CO_2$ emission cost will reduce significantly thereby Reducing Economic cost and enhancing the environment in relation to $CO_2$ emitted in Nigeria.

Comparing Business as Usual Scenarios with RES Scenarios, we observed that Increasing the percentage of RES in the energy mix (50%, 70%, and 90%RES) generally leads to both economic and environmental benefits compared to BAU scenarios.

The scenarios with higher RES percentages exhibit lower total annual costs, reduced $CO2$ emission costs, lower $CO2$ emissions, and a higher share of RE, indicating a potential shift towards a more sustainable and cost-effective energy future.

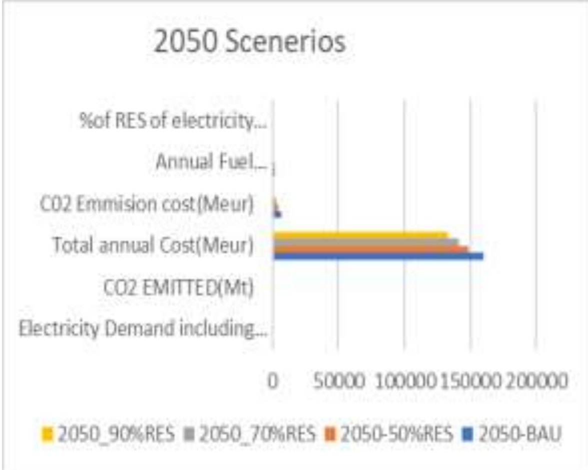


**Figure 4:** Energy for the Future in Nigeria Using RES 2050 Scenarios

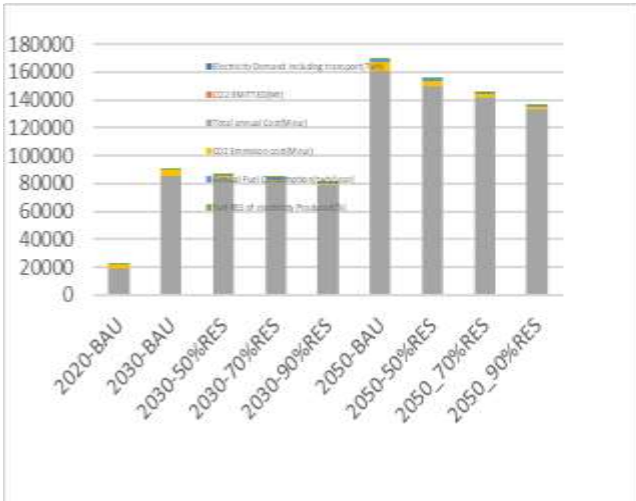


Figure 5: BAU and Renewable scenarios from 2020 to 2050

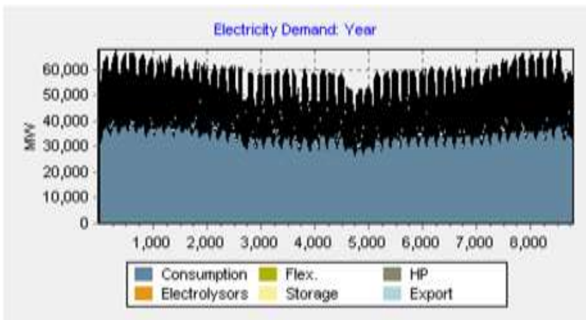


Figure 6: Electricity Demand

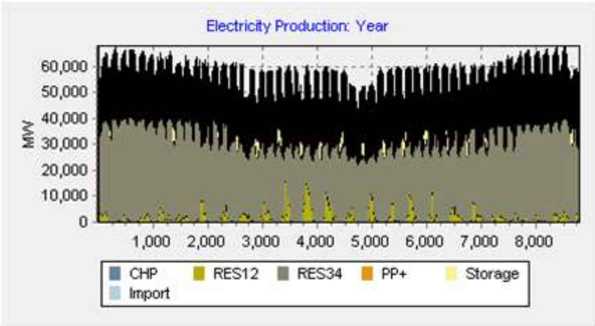


Figure 7: Electricity Production

Techno-Economic Analysis of Different RES for 2050 was presented in Figures 4,5 and 6. The wind energy is the independent variable and $C0_2$ Emitted is the dependent variable. Wind energy varies linearly with $CO_2$ Emitted. The gradient is negative indicting that as wind energy utilization is increased in the future in Nigeria, the $C0_2$ Emitted reduces which consequently makes the environment cleaner.

In figure 4.5(a) and Figure 4.5(b) it is advisable to increase Wind energy in the Energy mix of the future to a about 6000 MW considering the population and growth projection of Nigeria. Similarly, from figure. As the Wind energy supply is increased the Total Annual cost reduces and becomes optimal as the wind energy supply approaches 6000 MW.

In Figure.4.5(c) and Figure 4.5(d) below, Hydro Electric power increase leads reduction in CO2 emitted as well as the cost of C02 Emitted.

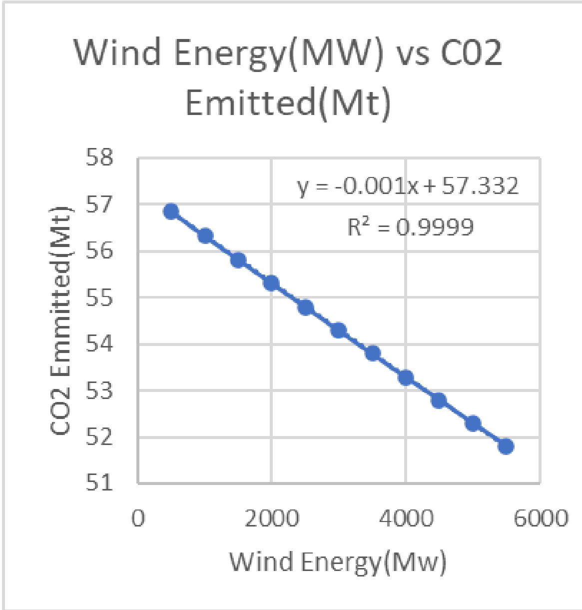


Figure 8:Graph showing the relationship between Wind Energy(MW) and CO2 emitted(Mt)

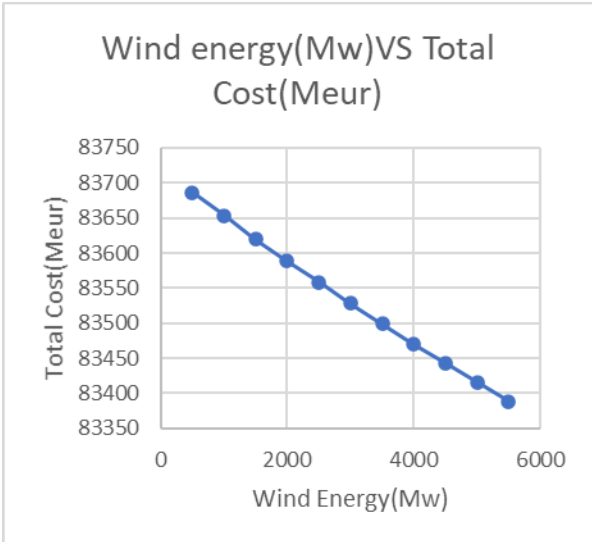


Figure 9: Graph showing the relationship between Wind Energy(MW) and Total Cost(Eur)

The relationship between hydroelectric power and CO2 emitted and total cost is linear until the energy supply hits 12000MW and start to flatten out as it approaches 15000MW and beyond hence it is advisable to keep the river hydro Energy supply on the energy mix to above 15000MW to optimise the efficiency of the energy mix. The negative linear correlation between hydroelectric power and total cost as well as CO2 emission is indicative of the cleaner and more sustainable nature of hydroelectric power. The fall in Total cost with Higher River Hydroelectric input suggest economies of scale where hydroelectric facilities benefits from lower average cost.

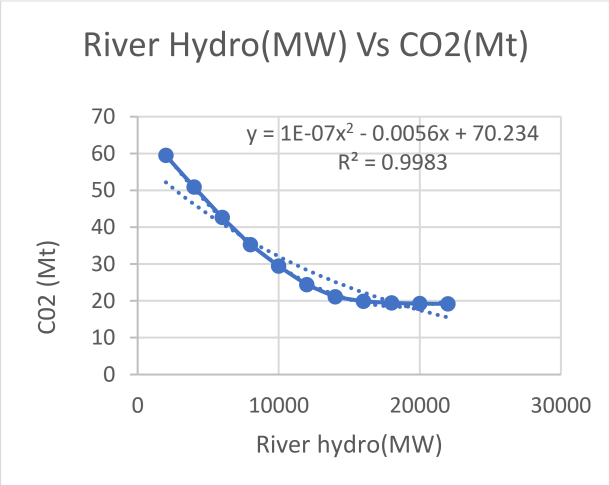


Figure 10: Graph showing the relationship between River Hydro Energy(MW) and CO2 emitted(Mt)

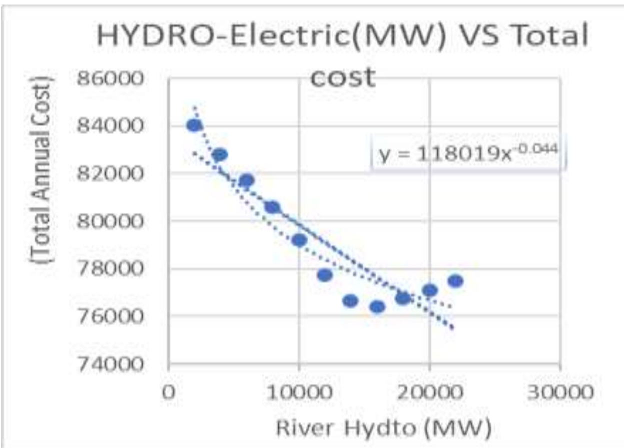


Figure 11: Graph showing the relationship between Hydro Electric(MW) and Total cost(Eur)

In the figure 4.5(e) and figure 4.5(f) below, as the Solar energy supply increases its CO2 emission reduces linearly to around 56(Mt) at around 6000MW of Solar energy Supply. For optimum design it is advisable to utilize at least 6000MW in the energy mix of the future. This trajectory is indicative of the fact that as we scale up solar energy supply, it is economical and more sustainable for the environment in Nigeria.

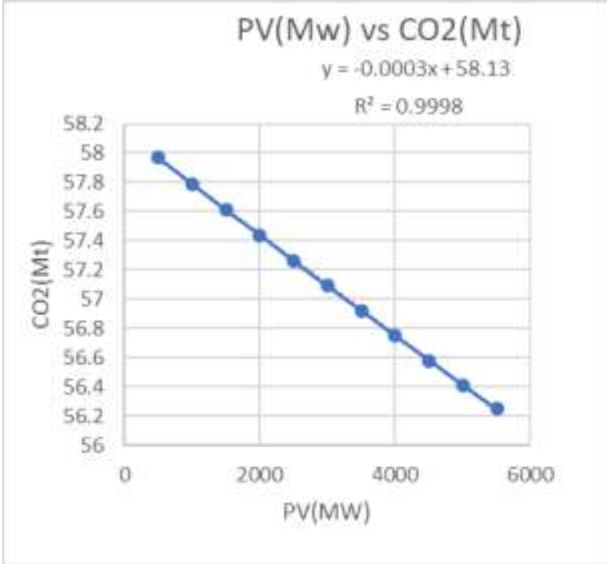


Figure 12:Graph showing the relationship between solar Energy(MW) and CO2 emitted(Mt)

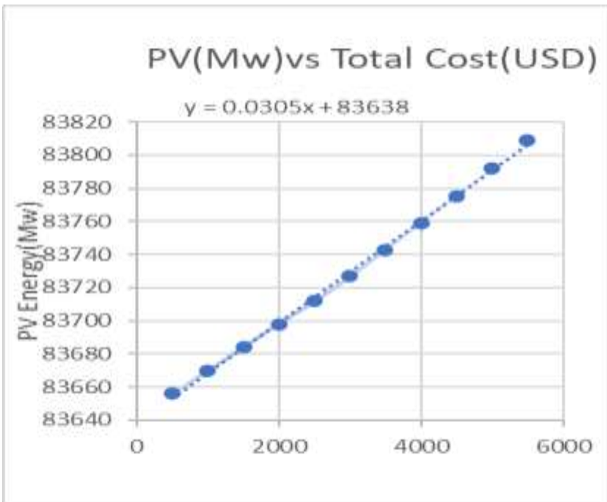


Figure 13:Graph showing the relationship between Solar Energy(MW) and Total Cost(USD)

Comparing the three sources of RE used for this study it cost 83670 Million euro to produce 1000Mw of PV energy, 83653 Million Euro to produce 1000 Mw of Wind

Energy and 84663 Million Euros to produce 1000MW of Hydroelectric.

Conclusively, based on annual cost of Production of RES, Wind energy is cheaper to produce however because the wind speed (2-9 m/s) in most regions of Nigeria is low, wind energy is not as readily available and reliable as hydro and solar power. Solar Energy on the other hand is not available and fluctuates all year long across the Nigeria based on location and seasons. Findings from this research it is advisable to scale up more on Hydroelectricity, followed by solar and lastly wind energy based on economics of scale, availability of water and dependability of Hydroelectric Technologies.

Summarily the three RES (Wind,PV and Hydro Electric) if scaled up from present Nigeria Electricity mix for residencial,commercial,inductrial and transport purpose will be more econonmical in terms of $CO_2$ Emmisions ,Fuel consumption and total cost thereby making the environment cleaner,heathier and meeting up with the targets of set in the Nigeria Energy transition plan.

**Table 6:** Cost difference from changing from Fossil fuel Vehicles to electric

| | | |
|---|---|---|
| $C0_2$ Emission of Petrol Vehicle | 4.2 | Mt $CO_2E$/vehicle/year |
| $CO_2$ Emission for Electric vehicle | 1.16 | Mt $CO_2E$/vehicle/year |
| Difference in $C0_2$ Emitted from converting petrol vehicle to electric | 3.04 | Mt$CO_2E$/vehicle/year |
| Cost of $C0_2$ | 28.6 | EUR/t$CO_2$ |
| Total cost Savings for converting 1 million passenger petrol vehicle/year to electric | 86944000 | EUR/t$CO_2$ |

Data Source:EPA(2023) &EnergyPlan(2023)

Thus, by converting 1 Million passenger cars to electric vehicles by 2050, we will reduce the CO2 emmsion by 3.04 Metric tons per vehicle per year which economically translate to a cost savings of 86.944 Million Euros per year.

## 5. CONCLUSION

As the Nigeria population increases, its energy demand and economic activities will also linearly increase. Thus, its current energy supply potential and the demand will surpass the energy supply. Thus, increasing the percentage of renewable energy sources (RES) in the energy mix (50%, 70%, and 90% RES) generally leads to both economic and environmental benefits compared to Business as Usual (BAU).

It is evident that from the results derived from all scenerios, it is possible for Nigeria to gradually replace fossil fuel from its energy mix with RES, as it is not only advantageous in terms of economics of scale, but also in terms environment sustainanibility by averting the attendant effects of $C0_2$ emmision (health, global warming etc. ) as well as they are readily available in abundance all year long. This can be done by converting about one million passenger cars to electric vehicles by 2050. Thus reducing $CO_2$ emmision to 3.04 metric tons per vehicle per year; which will economically translate to a cost savings of 86.944 million euros per year.

If the Nigeria Government intentionally invest in renewable energy (RE) infrastruture, continualy drive energy efficiency policies and is committted to implemenmt meticously the Nigeria Energy Transition Plan by 2050 , Nigeria can achieve 90 % RE in its Energy mix as findings from the Simulation from EnergyPlan in the studies by 2050 suggests.

In conclusion, this study observed the production of hydroelectricity should be scale up, followed by solar and lastly wind energy based on economics of scale, availability of water and dependability of hydroelectric technologies.

**Conflicts of interest**
The authors declared that there is no conflict of interest.

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