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Modeling the Next Decade of Energy Sustainability: A Case of a Developing Country

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Abstract: The development of any country is closely related to its ability to provide access to electricity for productive labor. Many countries in sub-Saharan Africa have low electrification rates for commercial, industrial and residential consumers. This study focuses on Nigeria, which has one of the largest populations and economies in sub-Saharan Africa. Although Nigeria possesses abundant renewable energy resources that can increase electricity generation, it has suffered a significant setback in electricity generation. However, for Nigeria to become one of the leading industrialized countries by 2030, access to clean, reliable, and sustainable energy sources is vital (Vision 20: 2030). This study assesses the possibility of Nigeria developing and transitioning to the use of various energy sources. Additionally, this study evaluates greenhouse gas (GHG) mitigation plans and future trends in energy sustainability through multi-criteria decision analysis (MCDA), considering the technical, social, economic, and environmental dimensions of the sustainability structure. A total of twelve (12) sustainability indexes were taken into consideration; these consist of two (2) technical, three (3) social, three (3) environmental, and four (4) economic indicators. A scenario-based software called Long-range Energy Alternative Plan (LEAP) was used to integrate the analysis criteria and forecast a sustainable energy generation mix for the future. It considered three scenarios, namely: the business as usual scenario (BAU); renewables, natural gas and biomass scenario (RNB); and renewables and coal scenario (REC). It was concluded that the renewables, natural gas, and biomass scenario (RNB) is the best scenario to solve Nigeria's energy problem based on the aim of the study.

Keywords: sustainability; energy transition; energy modelling; energy planning; multi-criteria decision analysis

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1. Introduction

Energy generation is a significant part of the fundamental issues for sustainable development [1]. Generating electricity in developing countries is challenging but essential for sustainable development [2]. In 1896, electricity was generated for the first time in Nigeria. Although Nigeria has existed for more than a century, the available electricity supply is much less than the current demand, thus negatively impacting the country's socio-economic and technological developments [1]. Nigeria remains the most populated country in Africa [3]. With an estimated population of over 211 million people as of 2021, only about 40% have a regular power supply [3]. Additionally, only 45% have access to the electricity grid, which is substandard and unsatisfactory.

Despite a tenfold increase in power consumption from 532 MW in 1972 to 6500 MW in 2005, the electricity supply remained much lower than the demand with an estimated 10,000 MW [4,5]. In the early 2000s, network transmission and distribution loss accounted for only 40%, and about 40% of the existing production capacity was not in operation. In 2003, for example, only about 3800 MW production capacity power of the 6500 MW installed capacity was available [4].

In 2019, Nigeria's population surpassed 200 million, and the current generation capacity is 7566.2 MW, with a total of 14,000 MW being installed. Nevertheless, only 5000 MW is available to consumers, with a renewable energy production of 15.71 percent. The rest of the power generation capacity is obtained from fossil fuels. This figure, based on the demand to supply ratio, is too small given Nigeria's potential to explore conventional and renewable energy. Over the years, renewable energy resources (RERs) potentials in Nigeria have been researched. It presented that African countries, including Nigeria, are rich in RERs, but the failure to make suitable renewable energy technologies (RETs) available is a major drawback in using RE [6].

Nigeria has diverse natural energy resources, including oil, natural gas, coal and lignite, wind, solar radiation, biomass, and nuclear energy [7]. In terms of natural gas reserves, Nigeria has the largest in Africa and the seventh-largest globally, but it is also suffering from economic turmoil and is termed a developing country due to its lack of electricity. Even with all of Nigeria's endowment, it has only been able to harness a tiny percentage of its potential, which risks an energy dependence of up to 85% on coal (fired gas) and 15% on hydroelectricity. Nigeria's economy relies heavily on the oil sector, which is not the best solution because its access is limited; therefore, it is not sustainable and cannot be relied upon.

Regarding Vision 20:20:20, Nigeria was said to have installed 28,000 MW capacity, fully functional generators to consumers that were still based on fired gas as the primary source of power generation, with just 4% being dedicated to renewable energy as of 2010 and 10% dedicated to renewable energy as at 2018 [7], with a GDP above USD 375.7 billion. However, to date, only 14,000 MW of power generation has been installed from 27 generating stations. According to reports from Vision 30:30:30, it is said that Nigeria is ready to invest in renewable energy and increase renewable energy generation capacity to 30% of the total power generation grid. However, we cannot be sure that these are not empty words. They have been repeated over the last two decades; therefore, this paper aims to analyze new technologies and energy to model suitable energy sustainability for Nigeria [8].

Ensuring the availability of clean, affordable, sustainable, and new-age energy for a nation's population is part of the United Nations (U.N.) Sustainable Development Goals. Sustainability goals are critical when considering human affairs and development within society. Energy sustainability is of great importance for all sustainable development programs, given the widespread use of energy, its economic growth and standards of living roles, and the significant effect of energy structures and systems on the environment [8,9].

Sustainable development is a modern goal that many nations worldwide wish for. There are many ways that global sustainability is described, and it is often seen as having three different components. To be termed a developed nation, it is imperative to comply with the rules and obligations of a foreign organization, for example, the U.N. Therefore, it is vital to meet the U.N. SDGs in particular to point out the best fuel mix for future generation systems is the "3E" assessment method, which takes into account the economic feasibility, environmental quality, and energy reliability (i.e., 3E) of the planned system proposed in the study by Imran Khan. Although the 3E method in the study considers only economic and environmental issues regarding sustainability dimensions, it does not take into account other essential sustainability dimensions [2,10].

Given this, a great deal of literature contains various suggestions on what can be carried out to help Nigeria expand its renewable electricity capacity. The creation of renewable electricity sources is fundamental to the world's future. In light of various efforts to strengthen and reform the energy sector, Nigeria's energy crisis, which has been going on for over a decade, is still profound. Nigeria's most practical energy source remains to be determined.

This research focuses on modeling the next decades of energy sustainability in Nigeria, with the intention that the provided solutions could be adopted as instrumental in shifting Nigeria from an energy-deficit nation to a nation with an energy surplus. The remaining sections are discussed as follows. Section 2 discusses the renewable energy and fossil-based energy potential in Nigeria. Next, a review of multi-criteria decision analyses and research on long-range energy alternative planning for energy systems is detailed in Section 3. The details of the model development, analysis, key assumption, and indicator selection are provided in Section 4. The scenarios developed for the analysis, as shown in Section 5, are reference scenarios (REFs) taking the year 2017 as the baseline: the business as usual (BAU); renewables and coal (REC); and renewable, natural gas, and biomass scenarios (RNB). Subsequently, the results are presented and discussed in Sections 6 and 7.

This study aims to answer these research questions: (1) Which criteria influence the choice of electricity generation sources for energy sustainability? and (2) Which alternative energy planning scenarios can be adapted to satisfy the energy demand and reduce greenhouse gas (GHG) emissions?

2. Literature Review

2.1. Renewable Energy Assessment

The authors of [11] analyzed how much renewable energy potential has been exploited in Nigeria and Cameroon and how this potential may hinder smooth implementations. Figure 1 shows the world's total energy increase, measured in quadrillion British thermal units (Btu) and based on economic goals and population increase [11]. It was found that wind, solar, and other RE sources had not been fully considered for incorporation into the grid as there is inconsistent budget allocation, a lack of structural development for technical and economic development, and inadequate technological know-how regarding the testing and maintenance of RE, likely due to their low power generation capacity as compared to other sources. Their study also analyzed the geographical location of Nigeria and Cameroon; the present condition of non-renewable energy in Nigeria; their potentials based on their short, medium, and long generation potential; and one of the important problems found in the privatization of the power sector, i.e., a lack of a licit structure to attract local and global investors [12].

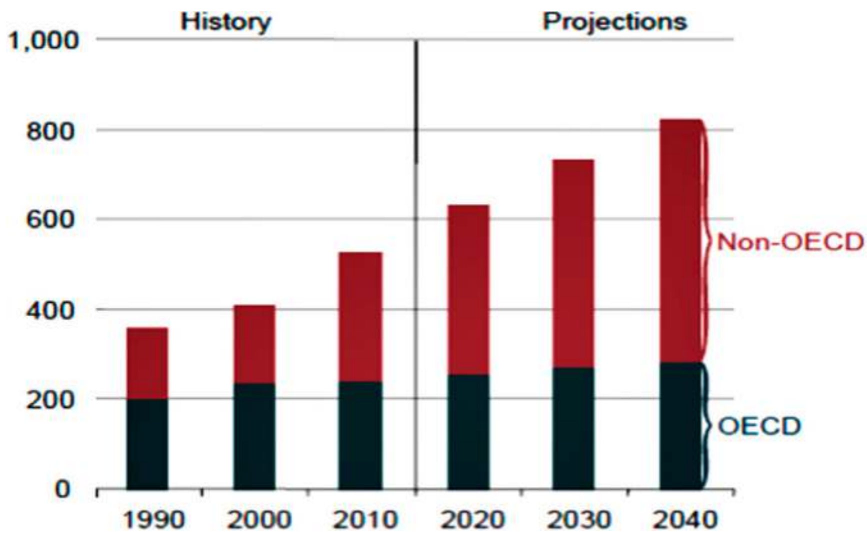

Figure 1. World energy consumption and estimates, in quadrillion Btu [11].

It is well-known that emissions from fossils fuels have led to a change in climatic conditions and depletion of the ozone layer, hence there is a need for sustainable energy development awareness. It has been projected that global GHG emissions will increase by 16% in 2040 by the authors of [13]. Thus, they explored ways that Nigeria can venture into sustainable energy development with low carbon emissions. It analyzed and identified other countries which had significantly exploited renewable energy, with Germany and the USA having exploited the most in renewables. The study showed several barriers to be considered when venturing into renewable energy generation as it has high costs and its supply is random, such that on a cloudy, windless day, both solar and wind generation are non-operational. Therefore, these authors suggested that, in order to effectively use renewables, technical requirements such as the reliability and continuity of energy must be factored into planning.

A discourse approach was used and suggested some ways to better the situation. These included using more precise and recent data to analyze progress in the renewable energy transition, ensuring policy coherence and stability, and having an in-depth knowledge of climate change and the renewable energy nexus [13].

2.2. Solar Energy Potential in Nigeria

Solar energy is derived from the sun and harnessed through photovoltaic, solar thermal energy, and solar architecture technology. Private residences and companies are where solar P.V. is installed and are primarily found in Nigeria, but its potential has not fully been exploited and implemented into the national grid [14]. In the literature [15], techno-economic activities have shown that solar P.V. is economically feasible in Nigeria. Nigeria's is located at the equator within a region where sunshine is spread evenly across the year [16] over a land area of 923,768 km^2 [17]. Solar radiation in Nigeria is estimated to be 12.6 $MJ/m^2/day$, as an annual daily average [16]. The sun's energy radiates at approximately 3.8×10^{23} kW per second. After passing through the atmosphere, a small region of the earth's surface can receive about 1 kW of solar power from the incident ray averaging 0.5 throughout daylight hours [18]. However, solar energy may be used in Nigeria for diverse purposes, such as powering areas not connected to the electricity generation grid, power supply to schools, and street lightning, etc. A recent study on the World Bank stated that 236 kW of solar mini-grid serves about 9000 people in Nigeria [18].

2.3. Hydropower Energy Potential in Nigeria

Hydropower is power derived from the energy of fast-flowing was or waterfalls. Hydropower is an already exploited technology in Nigeria and has been incorporated into the national grid. The hydropower potential in Nigeria is estimated to be 13,000 MW and 14,900 MW (Commission NER: Power generation in Nigeria) [19]. Many studies revealed that pumped hydro storage can serve as a renewable technology for storing electricity [19], such as photovoltaic, concentrated solar power (CSP), offshore, and on-shore wind power plants [20]. Large hydropower (LHP) contributes to about 28% of Nigeria's total energy generation capacity, making it a significant energy source as large rivers and waterfalls in the country are vital factors for primarily investing in hydropower [21]. Further research shows that hydropower is still very much under-exploited. Only 14% of hydro potential has been utilized, with Kanji, Shiroro, Jebba, and Zamfara being the major hydropower plants in Nigeria [12]. Challenges faced with the development of hydropower projects in Nigeria, as stated in [22], are a lack of research on intensive feasibility and technical knowledge for equipment manufacturing. A further study [18] compared small-scale hydropower plants and design generators based on their cost-effective potential. That study shows that the former is more cost-effective for rural electrification. Therefore, Nigeria needs to exploit more small-scale hydropower generation.

2.4. Biomass Energy Potential in Nigeria

Biomass energy is derived from living organisms, and it can be categorized into agricultural residue, municipal waste, wood waste, forestry waste, and industrial waste. This waste is then burned to generate heat that can be converted into electricity. Nigeria has a vast availability of biomass resources, and Adewale Allen's study found that 78% of the primary energy sources in Nigeria are from biomass. It is estimated that Nigeria has a biomass reserve potential of about 144 million tons per year. Plans for biomass exploitation in Nigeria are shown to contribute 1100 MW of electricity to the national grid [23]. Biomass potential in Nigeria is very promising, but Nigeria has failed to take advantage of its vast reserves such as the usage of food crops, as stated in [24]. It is a clean energy source that would be profitable to Nigeria as it does not involve irrigation and requires a small land usage, thereby creating a cleaner environment with the utilization of waste.

2.5. Wind Energy Potential in Nigeria

Wind power is a renewable energy source with little environmental impact and a clean source of energy generation, unlike fossil fuels that produce emissions. Wind energy has considerable offshore and on-shore potential in Nigeria. The study of [14] stated a high potential for offshore wind installation in the south and an on-shore potential in the north of Nigeria, above the equator [25]. Nigeria's wind usually varies from 1.4–10 m/s range depending on the location, and some locations have more wind than others [26]. Additionally, over 100,000 MW of wind power installation within Nigeria can be deployed [27]. Nigeria has not fully exploited the potential of wind energy and incorporated it into the grid as a source of electricity generation. However, a 4 kW wind turbine has already been installed and integrated into a 10 kW power plant [28]. A 5 kW wind system has been installed in Sokoto, and a 1 kW wind turbine has been installed in Bauchi and Kaduna for water pump purposes [22]. The wind speed, availability of wind turbines, and arrangement of the turbines are factors on which wind energy depends, though its energy generation could be estimated to be 70 to 85% [6].

2.6. Natural Gas Energy Potential in Nigeria

Natural gas plays a significant role in Nigeria's energy sources, as most new developments in power plants are based on gas-fired technology because of its current profitability [29]. Natural gas is one of the cleanest conventional energy sources contributing to nearly one-third of overall energy demand growth, more than any other fuel over the last decade. Nigeria has the second-largest natural gas reserve in Africa, behind Libya [30]. Natural gas has many advantages since gas turbines have a low annual cost, fast and easy maintenance, and high efficiency estimated to be 40% [31]. Though it is a convenient energy source, its environmental advantage is that it has fewer greenhouse gas emissions than other generation techniques. A study was carried out on the economic effect of natural gas consumption in Nigeria. It showed that an increase in economic growth is directly proportional to natural gas consumption [32]. In contrast, the nation's total energy consumption mix from natural gas has drastically reduced due to a lack of appropriate infrastructure for gas production.

2.7. Coal Energy Potential in Nigeria

Coal is derived from the remains of plant and animal matter, which usually decomposes over millions of years, eventually forming a brownish-black substance called coal that usually occurs in layers called coal beds. Coal was discovered in Nigeria in 1909. Coal mining in Nigeria started in 1916 with a reported production of 24,500 tons contributing to more than 70 percent to the country's commercial energy consumption [33]. Coal is expected to remain one of the dominant fuels in global electric power generation due to its low cost, reliability, and availability. However, due to the discovery of large oil and gas reserves, the Government decided to shift from exploiting coal to exploiting oil and gas. A study that analyzed the solution to clean coal in Nigeria further stated that Nigeria is rich in coal. However, due to the low annual coal production, which is just about 10,000 tons, we have not been able to harness and utilize coal for power generation despite Nigeria having an estimated coal reserve of at least 2 billion tons: approximately 190 million cubic metric tons.

The summary of findings in this section reveals that Nigeria is blessed with a quantifiable amount of all forms of renewable and non-renewable energy sources. As a result of this vast quantity, this study seeks to develop long-term energy planning scenarios that combine solar, wind, biomass, and coal energy sources.

3. Reviews on Multi-Criteria Decision Analysis (MCDA) and Long-Range Energy Alternative Planning (LEAP) for Energy Sustainability

The authors of [34] aimed to use a multi-criteria decision analysis to assess the effect of residential heating and household electricity consumption by resident, taking into account environmental and socio-economic criteria and testing the applicability of MCDA in the analysis of energy scenarios. They used an Irish city as an archive and evaluated six scenarios that corresponded to household and residential energy consumption. They based their analysis on energy consumption reductions and the development of renewable fuels and technologies. The analysis was conducted via a revised version of MCDA based on the NAIADE software, including a qualitative and quantitative assessment-based decision output. The result in the impact matrix format shows preferential policies that were presented by the NAIADE software. The most preferred approach was scenario two, which involves reducing energy and electricity usage, and scenario three, which involves a wood waste contribution and was the least preferred. A combination cycle of gas and steam turbines proved to be the best solution for all sets of criteria analyzed under each scenario.

The authors' aim in the study of [35] was to consider the best scenario to migrate from fossil fuels towards renewable energy, considering the adverse effects of CO_2 emission on the atmosphere. They analyzed four criteria: technical, economical, environmental, and social. In each criterion, the paper focused on certain aspects. For the technical criteria, it focused on efficiency, energy efficiency, the ratio of primary energy, and maturity. For the economic criteria, it focused on investment cost, operation and maintenance cost, and fuel costs. For the environmental criteria, it focused on gas emission, and for the social criteria, it focused on human/technological impact. The authors used the grey-based method in a multi-criteria decision analysis, a branch of grey system theory. Grey system theory initially aimed to analyze and optimize uncertainty issues. Grey relational analysis (GRA) accesses qualitative and quantitative factors. The GRA applied to the MCDA method can be classified into two major branches: analytical and predictive analysis. They also combined GRA with other methods, such as the fuzzy method and AHP. The most crucial criterion to consider is the technical criterion, and the most used sub-criterion is the energy system's efficiency. The environmental criterion is the most evaluated considering gas emissions (CO_2, CO, and NOx). Therefore, GRA was revealed to be a good tool for decision-making in energy systems, especially in cases where there is a shortage of information.

The study of [36] aimed to arrange Turkey's seven major electricity generation technologies in a hierarchy related to their performance scores in different sensitivity cases, using MCDA methodology to ensure affordable, reliable, and sustainable energy access to the masses. They had to consider an extensive range of economic, technical, environmental, and socio-economic criteria. Under these criteria are twelve indicators, with an electricity generation mix of coal, liquid fuel, hydro, natural gas, solar P.V., and on-shore wind studied between 2000 and 2016. They followed the following MCDA steps; (i) the description of the technologies for electricity generation to be tested, (ii) collection and evaluation of sustainability indicators, (iii) allocation of indicator weights in the specific sensitivity cases, and (iv) classification of electricity generation technology before further analysis. The main method in this research was a multi-criteria decision analysis. The Atilgan and Azapagic environmental impacts are calculated via the ReCiPe midpoint (H) methodology with SimaPro 8.2.0.0. software package; before the different criteria could be compared, analytical methods, distance-to-target methods, and linear normalization methods were used. Balin and Baraçlı explored alternatives to renewable energy via a fuzzy analytical hierarchy process (AHP) method based on fuzzy sets of type-2 and the decision making of multiple fuzzy criteria based on the type-2 interval technique in a preferential order for agreement with the perfect solution (TOPSIS) method. Seven power generation results were evaluated based on these primary energy sources and classified as hydroelectric, wind, coal, fossil fuel, and geothermal power plants, showing two results for wind energy, and another two for geothermal energy. However, it was concluded that hydroelectric power is the best choice for the most sensitive cases.

The study of [6] examined the ecosystem in Nigeria based on green energy to identify the gaps in energy demand compliance projected by the Energy Commission of Nigeria (ECN) and eventually made some recommendations based on the availability of diverse clean energy sources in Nigeria. It can be argued that RETs, particularly hybrid distributed energy systems, should be encouraged. It is undoubtedly appropriate for the Government to consider the potential use of the RETs to increase the nation's energy production capacity by 2050. It has been noted that Nigeria has potential in both non-renewable and clean energy sources. Important reviews on the present and future situations of RETs and how to harness renewables and biomass/bioenergy processes for low carbon production were conducted based to address this research gap. The studies discovered that conventional plants could work together with RETs.

In [37], Fernando Ribero et al. strategically analyzed long-term electricity decision-making problems and used a multi-criteria decision analysis alongside 13 other criteria, including social, environmental, economic, and technical issues. They compared different approaches: business as usual, natural gas power plant, new coal power plant, and hydro gas power plant. They came to the conclusion that, for a successful power generation and sustainability plan, the social effect must be paramount and be taken into consideration; the results show that hydro gas was the least sustainable solution out of all those tested.

In the study of [2], Leone et al. proposed the use of MCDA in the considered scenarios to evaluate different methods of electricity production. They attempted to evaluate future scenarios for power generation mainly dependent on coal power plants and increased renewables that cost more than coal, such as wind and hydro. They were able to use the MCDA tool to analyze various energy production scenarios considering 13 criteria covering economic, environmental, social, and technical issues. They used methodologies such as scenario generation and evaluation. They simulated different power technology scenarios based on various factors, such as economic (cost), social, environmental, and technical factors. They were able to predict and use MCDA tools to simulate a sustainable power system that could last until 2059; therefore, they concluded that hydro-gas is unsustainable.

Technologies such as combustion turbines, combined cycle, hydroelectric, steam turbines, steam cycle, or gasification, as well as nuclear, coal, and wind energy were considered. The capacity, base year output, each fuel percentage, peak capacity factor, as well as efficiency, are specified for each technology type. The authors used MCDA and considered five portfolios with natural gas playing a significant role. This paper attempted to prioritize portfolios involving investments in expanding energy capacity and energy security; therefore, it applied a multi-criteria decision model while primarily investigating the vastness of prioritization in more than one unpredictable and emerging scenario. The scenarios were identified by interacting with policymakers and stakeholder groups. This method defines which scenarios most affect portfolio prioritization and which of the portfolios has a larger potential for ups and downs across scenarios. The authors were able to ensure that all the five portfolios were constructed and installed, while taking economic viability into consideration. They also decided to increase the use of renewables from 10% to 20% and installed primarily nuclear power plants to solve their sustainability problems, which were analyzed using MCDA.

This paper of [38] aimed to illustrate the progression of MCDA methods, energy planning issues, and the application of MCDA and methodology. During the 1980s, the conflict between economic and environmental goals and awareness pushed energy planners toward using MCDA. They attempted to consider various MCDA methods and use them together. The combination of the ELECTRE-TRI method with other methods is particularly popular. A suitable integration of more than one method could be very advantageous. Such a combination could, therefore, help to exploit the strengths of the two methods. They were able to develop a sustainable power expansion plan through a combination of methods and processes. They used a value measurement method for which the most common approach is the multiple attribute value theory (MAVT) function. The selection of methods depends mainly on the preferences of the D.M. and the analysts. They proposed that each method's suitability, validity, and usability are should be considered in this study [39]; the aim was to build on the previous statistical analysis to determine favorable sites for on-shore wind turbines in Grusingh with the use of spatial multi-criteria decision analysis. The problem they addressed was the lack of effective planning for establishing wind turbines in areas that are socially unsuitable for their proper operation. They widely used GIS to capture, store, manipulate, analyze, manage, and present spatial or geographic data in combination with multi-criteria decision analysis (MCDA). They analyzed and evaluated three variables or indicators: (1) exclusion areas, (2) economic viability, (3) social acceptance, using techniques such as ELECTRE, the Weighted Sum System (WSM), and the Analytic Hierarchy Procedure (AHP). The results suggest that some factors influence planning approval, such as turbine capacity, a highly qualified percentage of the local population, political structures, and the operational duration of the turbine.

To support decision-making, this study's [40] objective was to critically consider energy storage technologies and provide an in-depth look into the existing MCDA literature related to it. This was achieved as one of the key components of a clean energy program through a systematic analysis of the MCDA literature on energy storage systems (ESS). They based their work on existing literature on the sustainability evaluation of grid-ties ESS using MADM and considered technological, economy, society, and environment indicators. The general overall method they used in this research paper was multi-attribute decision making (MADM), but sub-methods that were used for analysis were AHP combined with fuzzy logic and two further cases with PROMETHEE. The criteria considered under the economic indicator were economic performance, operating cost, technology flexibility, emission cost, and potential. Environmental criteria include: the lifecycle of production, disposal, and greenhouse gas (GHG) emissions. Technical criteria include: efficiency, energy density, autonomy, long-term storage application. Social criteria include: approval, impact on human health, or effects on job development. As a result, it was suggested that larger-scale installations and PHS technologies are promising. In most of the papers examined, lithium-ion batteries and other electrochemical storage technologies also score high but tend to be more focused on the application considered.

In the study of [41], the authors focused on proposing a sustainable development decision-making tool in Cameroon to select the best alternative from the number of pre-selected PHES plants. Therefore, they developed an MCDM methodology and considered three major procedures of the decision-making process, whereby three distinct methods under MCDM were incorporated into the process. The methodology that they used assigns weights to the decision variables and criteria of the decision using AHP's pairwise comparative approach. Meanwhile, the authors evaluated alternative performances based on a set of sixteen heterogeneous criteria grouped under three main indicators, namely: techno-economical, social, and environmental factors, and the authors used a rating system that includes fuzzy membership features and rating scales to resolve the vagueness of the language variables reflected in human preferences. Then, to aggregate the scored parameters, they used ELECTRE III, reputed as the least compensatory superlative MCDM process. This methodology makes the concept of strong sustainability possible compared to existing research, while addressing the heterogeneity of the criteria and a wider range of alternatives. The results show the usability and efficiency on a set of eleven PHES candidate sites in West Cameroon that were successfully tested. As a result, the top five alternatives take the form of renewable energy generation in the country.

In Turkey, Gulsan Yilan et al. [42] considered seven electricity generation technologies and aimed to rank them according to their performance suitability. They considered four factors, namely technical, environmental, socio-economical, and economic factors, and the electricity generation processes were natural gas, coal, hydro (dam and r-o-r), wind, geothermal, and solar P.V. They considered a total of 12 indicators and analyzed criteria such as installed capacity, annual production, and contribution to total production. In accordance with the guidelines of the International Organization for Standardization (ISO), they collected economic, technical, and socio-economic indicators from the literature and calculated environmental impacts through the life cycle approach. They used multi-criteria decision analysis (MCDA) to determine the order of alternative energy generation according to preference. The weighted sum method (WSM) approach was used in sustainable energy systems because of its straightforward nature. The results show that, for most sensitivity cases, hydroelectric technology with the dam is the most suitable scenario.

The aim of [14] was to model a cost-effective, green, and sustainable form of energy so that, by 2030, access to the electricity grid will be 100%. The study analyzed the use of natural gas (NG), on-shore wind (WON), offshore wind, photovoltaic (PV), and hydropower plants. The only ESS considered in this study was storage by hydraulic pumping. The combination of the above-mentioned technologies gave rise to a total of 99 distinct scenarios. The initial expenditure, overall costs of each year, =share of renewables, greenhouse gas emissions, and electricity output were analyzed for each of the scenarios. While other papers only focused on the generation aspect of Nigeria's energy instability, this study went further and focused on power transmission, stating that the major problem was reliability issues in transmission infrastructure due to several megawatts of power being lost in the process from generation to distribution. The stimulation method that was used in this study is a tool called the EnergyPLAN model, which is suitable for modeling future energy systems. The results show that the use of combined natural gas (NG), solar PV and wind on-shore (WON) to meet energy demands is the most sustainable plan.

Michael Harper et al. [41] aimed to explore how dependable biomass sources, such as biogas, and liquid biofuels, could be for Ghana in the future, basing their range on the year 2030 due to the challenge of using wood fuels as a main cooking gas, which emits GHG and fewer emissions than crude oil. The researchers conducted this study using the LEAP model. They considered energy scenarios, aggregation, and environmental databases and obtained their data from a detailed year when the last censor was taken. The sectors they took into consideration were household, agriculture, industry, transport, non-residential and street lighting, and greenhouse gas (GHG) emissions. The bioenergy fuels are considered to be biodiesel, ethanol, and gasoline, and the results show that the introduction of bioenergy as an energy source could reduce GHG emissions by around 6 million tons of CO_2 by 2030, which is, in turn, 14 percent less than the historical scenario.

The aim of the study of [5] was to analyze current problems with energy generation, so as to plan for 20 years of government expansion. This included the implementation of new technologies for energy generation, which were not used for the start year analysis, it considered the different electricity generation methods and the total demand forecast of 3 different scenarios (scenarios 1, scenarios 2, and scenario 3) for electricity. The authors used long-range energy alternative planning (LEAP) for its simulation and it showed that, for Scenario1 using the REF scenario, the total electricity required is projected to be about 59 gigawatt hours by 2020, rising to almost twice this level by 2030.

The authors of [42] aimed to forecast the supply and demand of electricity for a time period between 2010 and 2040 to solve sectorial energy problems. The operational cost, electricity index, and emissions were the major factors compared in each of the three scenarios. How the energy system would develop, starting from the base year and considering the above-mentioned factors was what they looked into in the following scenarios: business as usual (BAU), energy conservation (E.C.), and renewable energy. They used the long-range energy alternatives planning (LEAP) model to simulate this scenario. The results show that, in the BAU scenario, urban population access to electricity would increase the number of nuclear plants, expansion of hydro and gas power plants; the transmission losses would remain the same. In the E.C. scenario, efficient lighting would be used; energy-efficient technology would increase, thereby conserving energy; and transmission losses would reduce. The REN scenario entails a transition of potential power plants that utilizes renewable sources and prevents the use of gas power plants in the future. The E.C. scenario is preferred because energy demand and losses in energy transmission and distribution were greatly reduced due to the introduction of energy-efficient measures for this scenario.

The objective of [43] was to use a methodological approach to help directly and reflectively formulate, evaluate, and promote the energy policy of a country with valid research and objective evaluations. It used a multi-criteria decision analysis to investigate and select elements of energy policy and considered a total of 24 sub-criteria divided into 5 dimensions, namely: technical, economical, social, environmental, and policy/regulation dimensions. The long-range energy alternative planning (LEAP) model was used for this study, where every analysis criterion was evaluated in four scenarios, namely: reference (REF); business as usual (BAU); renewables and coal (REC); and renewable, natural gas, and biomass (RNB) scenarios. The results from the graph show that the REN-b was the best alternative, with a 6% acceptability higher than the REN policy scenario at 32%. It was considered the next-best alternative, and ECET was the least preferred scenario.

In [44], the authors aimed to analyze the supply and demand of electricity so as to attain an equilibrium between them and to transition from a dependence on imported fuels for power generation. They considered four supply scenarios: reference (REF), renewable energy technologies (RET), clean coal maximum (CCM), and energy efficiency and conservation (EEC), taking into account the potential of resources, techno-economic parameters, and CO_2 emissions. They considered various power plants to achieve their aim, such as oil, nuclear, solar, wind, biomass, large hydro, etc., with indicators such as capacity (MW), efficiency, generation, fixed cost, variable cost, maximum availability, capital cost, and consumed fuel. The method they used was long-range energy alternative planning (LEAP), where they made key assumptions regarding domestic, industrial, commercial, and agricultural consumption. The study shows Pakistan's estimated total electricity demand in 2050 is expected to be 1706.3 TWh, which in 2015, was just 90.4 TWh. As such, the results show an average growth of 8.35% for each year and projected growth to be 19 times higher than the demand in the base year.

One advantage of multi-criteria decision analysis (MCDA) over other techniques is that it measures a wide range of factors affecting the decision-making process in environmental policy [45]. Rather than focusing on a single parameter utilized in conventional tools such as a cost–benefit analysis (CBA) or environmental impact assessment (EIA), MCDA explores the full range of impacts of a policy or project [34]. Additionally, unlike other reductionist techniques, MCDA often leads to more optimal results because of its multidimensional nature. More advantages of MCDA over other techniques can be found in reference [34]. When setting up an MCD analysis, a researcher may undertake the following steps: (i) defining and structuring the nature of the problem or decision, (ii) generation of possible alternative scenarios, (iii) determination of evaluation criteria or indicators, (iv) normalization of evaluation criteria or indicators (v) selection of data type, e.g., discrete or continuous data and data collection type, e.g., quantitative data or qualitative data (vi) determination of indicator weights used to determine ranking relations (vii) evaluation of results by determination of the order of preference of the alternative scenarios (viii) sensitivity analysis [34,42].

Based on the literature review, in developing a model in LEAP for Nigeria's energy planning scenario, this study includes the economic, technical, environmental, and social parameters to select the required indicators. Similarly, this study developed energy planning scenarios from 2017 to 2040.

4. Materials and Method

4.1. Model

In this section, the modelling of a long-term energy sustainability plan for Nigeria is presented. It is divided into four sections. The first section comprises a presentation of the simulation software algorithm, inbuilt variables requirements, formulae, and functions of the different tags in the LEAP software environment. The next section describes how the leap software environment was used to achieve the aim of the study. The last two sections present the multi-criteria decision analysis that was considered for the project simulation, development of the scenario, analysis of the results and reasons for using the LEAP software. The energy sector faces so many challenges, encompassing technical, environmental, socio-cultural, and political barriers. A simulation of future development of sustainable energy generation, the greenhouse gas (GHG) effect and energy demand to supply requirements were taken into consideration. This was carried out using the LEAP model interface. In this study, six different fuel types projected to be suitable for Nigeria's energy sustainability were considered, namely: coal, natural gas, hydropower, biomass, solar, and wind energy. Data on assumptions and greenhouse gas emission for Nigerian can be retrieved from References [46–49].

4.2. Scenario Evaluation Tool: LEAP Model

LEAP, developed at the Stockholm Environment Institute, is a commonly used software tool for an energy forecast analysis and climate change mitigation assessment. It is a scenario-based modeling methodology that takes into account both research in energy sectors and non-carbon GHG emission sources, as well as climate change mitigation assessment. It is a great tool for developing models of various power systems, each of which requires a unique data structure. LEAP, with its energy accounting capabilities, adapts to the demand for energy production from the supply side and offers system impact metrics (criteria) such as energy generation from sources, installed capacity requirements, environmental emissions, cost of production, etc.

The LEAP model is made up of four modules: key assumption, demand, transformation, and resources. LEAP is a responsive software that allows users to easily interact with its flexible data structure. LEAP is technologically rich and has inbuilt energy planner information.

4.3. Analysis

The photos are stacked above each other, and the analysis photo is the first from the top. This is used to create a data structure for the simulation area by editing the tree in the left of the photo, which is organized into categories of information, with sub-criteria being modeled so that they align the study objectives.

4.4. Key Assumptions

The key assumption branch is where user-defined variables are created. It can vary based on the scope of the study. Any assumption created is organized into key assumptions in a hierarchical data structure. The assumptions used for this study are income, population, household size, household, household, GDP, income growth rate, population growth rate, and end-year urbanization. Scales and units are also specified for each of the data sets, which is in reference to the base year (2017). Statistical data for Nigeria can be retrieved from references [50–58].

4.5. Indicator Selection

Four modules under the indicator branch are created based on the proposed analysis, namely: economic indicators, technical indicators, environmental indicators, and social indicators. A total of 12 user-defined variables are considered across each of the indicators. Some of the specified criteria cannot be measured on a quantitative scale and therefore have no units. Based on merit, an ordinal scale of 1–4 (with 1 being the poorest value and 4 the best value) is assumed for these criteria.

1. Economic indicators: This indicator branch considers a capacity factor, the resource availability, electricity generation cost, and operating/maintenance cost of each process;
2. Technical indicators: Two criteria were developed for this indicator, which considers how efficient and reliable the processes are for generating energy;
3. Environmental indicators: This indicator considers the environmental aspect of energy generation in Nigeria. It looked into the impact of GHG emissions from such processes on the environment, land use, and soil pollution;

4. Social indicators: People displacement, public acceptance, and new job creation were the three criteria selected for this indicator and were all measured based on the assumed ordinal scale (1–4).

5. Scenario Development

The scenarios were formulated based on the Nigerian Government's planned energy expansion and greenhouse gas (GHG) mitigation options. A total of four scenarios that span the period from 2017 to 2040 were formulated. The current situation and future trends on how electricity will be generated and consumed were incorporated into the scenarios. The scenarios created for this study are the reference (REF); business as usual (BAU); renewables and coal (REC); and renewable, natural gas, and biomass (RNB) scenario. The reference scenario is used as the benchmark or baseline for the other three scenarios (BAU, RNB, REC). It also takes into account all of the current expressions and historical calculations, which this study uses for its chosen base year of 2017. The MCDA indicators for each scenario is provided in Table 1.

Table 1. MCDA indicators for each scenario.

Criteria	BAU	REC	RNB
Capacity factor (%) [2]	70	75	81
Availability	2	4	4
Generating cost (thousand USD/year)	3199	3005	3284
Soil pollution	1	3	4
Efficiency (%) [3]	50.5	74	80
CO_2 [4] (million Mtoe)	86	81	80
Land use	4	1	2
Displacement	4	1	2
Reliability (%).	50.5	45	42
Job creation	1	3	4
O/M cost (thousand USD/year)	0.12	0.09	0.10
Public acceptance	1	3	4

5.1. Reference Scenario

In the reference scenario, it is assumed that no new energy policy intervention or modification is applied but the policy strategies of alternative scenarios are increased. The dataset for the calculation process may be used for a single base year or historical trend base year, whereas the key assumptions and relevant data used in this current account are for a single base year. Regarding the key assumption for the base year of 2017, the population data retrieved from the World Bank is set to 191 million people, income growth rate is 0.83% [50], household size is 6 people [51], the household is set to 40.5 million people [52], GDP is USD 375 billion [53], population growth rate is 2.64% [54], and end-year urbanization is 49.52% [55]. Under the demand modules, household, industry, transport, and commercial percentages of total energy consumption are set to 30%, 5%, 50%, and 15%, respectively [56]. Data for the key assumptions for the base and end year are detailed in Table 2.

Table 2. Key assumption parameters for the Nigerian LEAP model for the base and end year.

Key Assumption	2017	2040
Income (thousand USD/yr)	3000.0	3858.2
Population (million)	191.0	343.1
Household Size (people)	6 [5]	5
Households (million)	40.5 [6]	73.6
GDP (billion USD)	375.7 [7]	1515.0
Income growth rate (%)	0.83 [8]	1.4
Population growth rate (%)	2.64 [9]	2.58
End Year urbanization (%)	49.52 [10]	62.4

5.2. Business as Usual (BAU) Scenario

The business as usual scenario is similar to the reference (REF) scenario derived from the current account. This scenario projects that a normal energy policy is implemented over the years, which exploits fossil fuels and hydropower as compensation for the degradation of coal, where fossil fuels constitute 85% of the total electricity generation and hydro comprises the remaining percentage, according to World Bank. The scenario was developed based on energy demand and supply, greenhouse gas emission forecast, and the cost of production. The already defined key assumption data are used as a reference for this scenario. This scenario made the following assumptions under the key assumption branch: the population in the reference year grows at a rate of 2.58% up until the end year, the GDP is USD 400 billion according to WDI (world data indicator), gross national income (GNI) growth rate is 2.28%, and household size decreases to 5 people per household from the base year (data were retrieved from Tradingeconomics and Macrotrends, respectively). Parameters for process efficiency and losses of the fuel types (natural gas, solar, coal, biomass, hydro, and wind) were derived from [46] using the energy conversion rate and capacity factor, and total transmission and distribution losses remain at 16.11%. This scenario is considered without considering the GHG mitigation plan and assumes that the historical trend of energy production is derived from increasing hydro and fossil sources. The BAU scenario was used as a benchmark for comparing the two other scenarios in terms of cost and GHG emissions.

5.3. Renewables, Natural Gas and Biomass (RNB) Scenario

This scenario was developed taking into consideration the need to improve energy generation by 2040 with a significant change in the rate at which greenhouse gases are emitted from the REF scenario. To achieve this, this scenario considered exploiting renewable sources, incorporating new energy generation fuels, and increasing the already existing natural gas plants energy capacities. It is assumed in the household sector that more efficient lighting and cooking fuels will be used, and efficient refrigeration will increase by 20% from the BAU scenario. In the industrial sector, the end year consumption of coal is reduced by 30% from the base year, which was 418,680 GJ/Mtoe [57]. Electricity generation was calculated in gigawatt hours, and it is assumed that renewables will grow at a rate of 15% and natural gas at a rate of 2% compared to the historical production rate in the reference scenario [58].

5.4. Renewables and Coal (REC) Scenario

This scenario considered exploiting renewables and coal as the fuel processes that could help Nigeria address its energy demand and supply situation [59]. In this scenario, it is assumed that the exploitation of coal increases at a rate of 10% per annum from the BAU scenario, and renewable energies are incorporated into the grid, with hydro and biomass being the most exploited renewable process for this scenario. The key assumption expressions remain the same as the current account. For mining in the industrial sector, the consumed energy is coal, which is maintained at 80% under the activity level variable. It was assumed that a 7000 MW production capacity for a coal power plant is to be installed at the end of the base, and other conventional sources used in the business as usual scenario are considerably reduced. Under the electricity generation branch, the processes dispatch rule expressions were set to the following functions: MeritOrderDispatch, ProportionalToCapacity, and PercentShare.

6. Results and Discussion

This section presents the results obtained from the three developed scenarios—BAU, RNB, and REC—by considering 12 criteria integrated into the LEAP software. The results are analyzed based on the different scenarios, and interpretations of the results are presented in the following order: electricity generation by output fuels, energy demand of each scenario, electricity generation capacity, GHG emissions, and comparison between scenarios.

6.1. Electricity Generation by Output Fuels

The results show the annual energy production of the transformation and generation module considering all fuel types for each of the scenarios. In the simulation stage, expressions based on capacity variables were inputted and the base year 16.11 percentage loss was factored in to meet the planning reserve margin in reference to the electricity policy of Vision 30:30:30 [23]. As shown in Table 3, the RNB generates the highest amount of electricity for any scenario. This improved the electricity generation by a total of 18.05% from the BAU scenario in the end year and REC scenario by a total of 12.94%. Table 3 shows the progression of the results in gigawatt hours.

Table 3. Electrical output by scenario.

Scenarios	2020	2025	2030	2035	2040
Business as usual	103.3	104.9	106.5	108.1	109.7
Renewables, natural gas and biomass	110.4	116.3	122.1	127.9	133.7
Renewables and coal	105.5	110.6	115.8	121.0	126.1

6.2. Energy Demand by Scenario

The results show the final energy demand based on the assumptions of each scenario by each of the sectors in the analysis view. According to the World Bank, the household and transport sector in Nigeria demands the most electricity; therefore, these sectors were was used as a reference in the current accounts. The results show that energy demand will continue to increase in each scenario but at different rates. Compared to the BAU scenario used as reference, the RNB scenario, as shown in the graph analysis, was able to reduce the total energy demand of each sector by 40% in the end year and REC by 37%. The progression of the results is shown in Table 4.

Table 4. Energy demand by scenario.

Scenarios	2020	2025	2030	2035	2040
Business as usual	112.3	137.6	167.4	202.5	243.7
Renewables, natural gas and biomass	103.4	111.6	121.0	131.9	135.2
Renewables and coal	105.3	116.5	128.6	142.2	152.4

6.3. Electricity Generation by Scenario

The results show the capacity of the processes in the transformation module categorized for each scenario. The expression inputted for variables in the transformation branch, such as exogenous capacity, endogenous capacity, historical production, and capacity credit influences the outcomes of the processes. Table 5 shows that the electricity generation capacity of the BAU and REC scenario increased from an average of 14.2 thousand megawatts to 14.9 and 18.0 thousand megawatts, respectively.

Table 5. Electricity generation capacity.

Scenarios	2020	2025	2030	2035	2040
Business as usual	14.1	14.3	14.5	14.7	14.9
Renewables, natural gas and biomass	14.8	16.2	17.5	18.9	20.2
Renewables and coal	14.5	15.4	16.3	17.1	18.0

The analysis shows that the renewables, natural gas, and biomass (RNB) scenario has a higher generating capacity than the other scenarios, and as shown in Table 5, it was able to reduce the total energy demanded by each sector, thereby making the supply of energy meet its demand. The renewables and coal (REC) scenario also surpassed the electricity capacity of the BAU scenario by 18.13%, but it was still lower than RNB's scenario generation capacity.

6.4. GHG Emissions

GHG emissions are an environmental effect, and the results for environmental effects can only be obtained if "Energy Sector Effect Loading" is checked in the basic parameter tag during the simulation. Table 6 shows the GWP (global warming potential) of CO_2 for each scenario up to 2040. Data retrieved from IEA estimated the base year total emission as 86.0 Mtoe of CO_2; therefore, as shown in Table 6, the continuation of the BAU scenario will lead to a 63.6% increase in total CO_2 emissions by the end year, REC and RNB will decrease the total emission of the BAU by 31.21% and 40%, respectively. Biomass (RNB) scenario starts to decrease the rate at which GHGs are emitted by 0.53% from 2035 to the end year. Therefore, it can be estimated, as shown in Tables 6 and 7, that there will be a higher energy generation with a lesser rate of GHGs emissions after 2035 with this scenario.

Table 6. CO_2 emissions from each scenario.

Scenarios	2020	2025	2030	2035	2040
Business as usual	101.2	134.0	173.6	221.1	278.0
Renewables, natural gas and biomass	92.7	106.3	119.7	132.9	132.2
Renewables and coal	93.5	108.6	124.1	140.2	149.4

Table 7. Total 100-year GWP emissions from each scenario.

Scenarios	2020	2025	2030	2035	2040
Business as usual	28,859.3	35,233.4	42,735.8	51,546.5	61,872.5
Renewables, natural gas and biomass	26,571.7	28,594.3	30,959.6	33,707.3	34,587.4
Renewables and coal	27,098.3	29,885.9	32,937.9	36,371.2	38,981.1

Table 7 shows the total GHGs emissions of all gases, including CO_2 methane, nitrous oxide, and CFC-11 for the fuel types in each scenario measured in metric tons CO_2 equivalent.

6.5. Comparison of Scenarios

Tables 6 and 7 show the GHGs emissions for the BAU scenario and the RNB and REC scenarios, respectively. It projects the rate at which emissions from all fuels, tags, and processes could be reduced if the developed scenarios are considered. It shows a clear and detailed comparison of the GHG between the two alternative scenarios developed. It shows that RNB has a better mitigation effect on GHG emissions as it reduced emissions by 11.2 percent more than the REC scenario in the end year, as shown in Table 7.

The RNB scenario is proven to be the best scenario based on the aim of this study, meeting energy supply and demand requirements at a reduced GHG emission rate and a considerably lower cost than the BAU scenario. Alternatively, considering the cost of production, the REC scenario seemed to generate more energy at a reduced cost in the future in comparison to the RNB scenario but at higher GHG emission values, as shown in Table 8.

Table 8. Cost of energy production from each scenario in million USD.

Scenarios	2020	2025	2030	2035	2040
Business as usual	3250	3437.5	3750	3937.5	4250
Renewables, natural gas and biomass	3315.5	3375	3375	3250	3248
Renewables and coal	3000	2875	2750	2375	2000

7. Conclusions

This study aimed to model a sustainable energy plan for the future of Nigeria. It highlighted the energy challenges that Nigeria faces, some of the causes of these issues, and a way forward. The study also presented a review of other studies faced with similar challenges and previous measures that were taken. This study used a multi-criteria decision analysis (MCDA) and long-range energy alternatives planning (LEAP) to actualize this aim. It considered decision analysis criteria and how this was integrated into the LEAP software to find the most suitable scenario of fuel combination for sustainable energy generation in Nigeria. This study integrated 12 indicators that address economic, technical, environmental, and social constraints. Similarly, this study assessed the results of integrating biomass and coal energy sources into the proposed energy combination for Nigeria. The introduction of biomass and coal has not been fully explored as a solution to energy planning in Nigeria due to a lack of available data. This study concluded that the best possible scenario for meeting energy demand with the lowest possible greenhouse gas emissions and a reduced energy cost is the renewables, natural gas, and biomass (RNB) scenario. We suggest that energy policy makers in Nigeria consider expanding the current power generation systems to include more renewable energy sources such as wind, solar and biomass. Of course, the integration of renewable energy to the national grid comes with some challenges. However, these challenges pale in comparison to the benefits accrued from the sufficient energy production for productive labor.

The major achievements recorded in the development of this sustainable energy model were based on the achievements of this study, which are:

1. The criteria that influenced the choice of electricity generation via a multi-criteria decision analysis were duly and successfully acquired and grouped into four sustainability indices.
2. Various alternative energy sustainability scenarios were developed and successfully compared to achieve the goal of this study.
3. The LEAP software was successfully used to develop a sustainable model that meets energy demand at a reduced GHG emission rate.
4. MCDA criteria were successfully integrated into the LEAP software, and the compared variables were properly described and graphically illustrated.
5. The best-performing scenario containing a fuel mix of natural gas, renewables and biomass energy for efficient and sustainable energy from 2017 to 2040 was determined.

Current long-term energy planning studies in Nigeria focus on centralized power generation solutions. An important future research direction includes developing a decentralized energy generation for Nigeria, where all sub-regions in Nigeria can independently produce the electrical energy required for their region [60]. Furthermore, future studies should assess the future demand of key service industries in Nigeria with a view to providing feasible energy solutions for the productive sector. Sectors such as education, transportation, and health have not garnered enough attention in the literature.

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