Energy Strategy Reviews 44 (2022) 100962

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system

Hanif Auwal Ibrahim [*,1], Michael Kweneojo Ayomoh

Industrial and Systems Engineering Department, University of Pretoria, 0028, Hatfield, South Africa

ARTICLE INFO

Keywords:
Multi-objective optimization
Power
Sustainability
Economic
Emissions
Job creation
Renewable energy
Energy modelling

ABSTRACT

The ever-increasing demand for electricity, as well as its impact on the environment, necessitates expanding the power generation mix of Nigeria by utilizing sustainable energy sources. Power generation planning that is sustainable and efficient must meet various objectives, many of which conflict with one another. Using multi-objective optimization, a model for Nigeria's power supply architecture was developed to integrate indigenous energy sources for a sustainable power generation mix. The model has three conflicting objectives: reducing power generating costs, reducing CO_2 emissions, and increasing jobs. Hybrid Structural Interaction Matrix was utilized to compute the weights of the three objectives for the multi-objective model to be modified into a single-objective model. According to the simulations, Nigeria could address its power supply deficit by generating up to 2,100 TWh of power by 2050. Over the projected period, large hydropower plants and solar PV will be the leading option for Nigeria's power generation mix. Furthermore, power generation from solar thermal, incinerator, nuclear, gas plant, combined plant, and diesel engine will all be part of the power supply mix by 2050. In terms of jobs expected to be created, about 2.05 million jobs will be added by 2050 from the construction and operation of power generation plants. CO_2 emissions will attain 266 M_tCO_2 by 2050. The cost of power generation will decline from a maximum of 36 billion US$ in 2030 to 27.1 billion US$ in 2050. Findings conclude that Nigeria can meet its power supply obligations by harnessing indigenous energy sources into an optimal power supply mix.

1. Introduction

A sustainable power supply mix entails meeting today's power requirements while not risking future generations' capacity to achieve theirs [1]. Since its inception and implementation, sustainable development has been the subject of a plethora of research on various themes, levels, and viewpoints [2]. Nigeria must solve its problem of inadequate power supply to stay competitive and relevant among nations, especially as the COVID-19 pandemic has wreaked havoc on the economy [3]. Nigeria, fortunately, has a diverse abundant range of energy sources from which to draw and establish a sustainable power supply mix that would satisfy the growing power demand, conserve the environment, and reduce greenhouse gas (GHG) emissions [4]. Despite its abundance of power-generating sources, Nigeria is struggling to fulfill its rapidly increasing power demand and is plagued by rolling blackouts in most parts of the country [5]. Electricity is available to just 55.4% of the population, with electrification rates lower in the east and rural areas [6].

The utilization of RE (renewable energy) sources is regarded as a crucial component of sustainable energy systems [7]. The major challenges confronting Nigeria such as unemployment and security threats will all be addressed through industrialization and this can only be achieved by steady, economical, and environment-friendly power supply [6].

Policymakers and researchers who want to develop an environmentally friendly power supply system need to use energy modelling and optimization techniques to ensure that different objectives such as cost, emissions, jobs, etc., are met [8]. Modelers have been developing optimization models of energy systems since the 1990s [9–13]. Costs or emissions are optimized to develop optimal power supply mixes for regions, cities, and nations [14–22].

Abbreviations: PP, Power plant; HSIM, Hybrid Structural Interaction Matrix; HTSD, Hierarchical Tree Structural Diagram; PES, Power Energy System; MCDM, Multiple-Criteria Decision-Making; GHG, Greenhouse gases.

* Corresponding author.

E-mail address: hanif.ibrahim@tuks.co.za (H.A. Ibrahim).

[1] Lead Contact.

https://doi.org/10.1016/j.esr.2022.100962
Received 31 May 2022; Received in revised form 10 August 2022; Accepted 5 September 2022

Nomenclature

$f1$	Electricity generation cost objective function, (US$)
$f2$	CO_2 emissions objective function for energy sources, (M_t)
$f3$	Jobs objective function, (%)
$f4$	Multi-objective function with three objectives
$w1$	Weight of cost objective function
$w2$	Weight of CO_2 emissions objective function
$w3$	Weight of job creation objective function
G	Power being generated, (MWh)
$sLCOE$	Simplified Levelized Cost of Electricity, (US$/MWh)
r	Discount rate
C	Capital expenditure of newly installed power plant, (US $/MW)
O	Operating and maintenance costs, (US$/MW, US$/MWh)
F	Fuel cost, (US$/MWh)
$\mathcal{E}$	Power plant heat rate/thermal to electricity efficiency
CRF	Cost recovery factor
Cf	Capacity factor
$\varnothing$	Learning rate elasticity
N	Cumulative capacity
CO_{2EF}	CO_2 emission factor, (ton CO_2/MWh)
D	Electricity demand, MWh
F_s	Fuel supply, (MWh/year)
i	Index for technology type
t	Index for a time horizon
new	Index for new power plant
ext	Index for existing power plant
Fix	Index for a fixed value
Var	Index for variable value
b_i	Jobs created in construction phase of the power sector by technology i (GWh)
h_i	Jobs created in operation phase of the power sector by technology i (GWh)
X	Net electricity generation (MWh)
ρ	Self-consumption of technology (%)
ω_i	Maximum share of technology (%)
CT	Construction time of technology (Year)
$INVC$	Investment cost of technology ($/MW)
NAC	Newly added capacity of technology (MW)
bgC	Budget required for constructing new capacities ($)

Power planning has become a complicated issue involving several factors due to the relationship between electricity consumption, protection of the environment, economic growth, and civic responsibility [23]. As a result, approaches for energy modelling and optimization that can integrate numerous objectives to develop a power policy are of great importance. Determining the optimal power generation mix that will fulfill electricity demand whilst fulfilling numerous limitations is the fundamental modelling concept behind long-term energy planning. Some important outputs of such techniques include the kind of power technology used, the quantity of installed power capacity, time to develop and operate the technology, and necessary fuel sources. Numerous studies looking at the socio-economic optimality of power planning have focused on using cost optimization models like MESSAGE, MARKAL, TIMES, etc. (see, for example, Refs. [24–33]). The strategic planning of power planning systems, on the other hand, inevitably incorporates several competing objectives [34–36]. Previous studies on multi-objective optimization addressed environmental or social objectives by transforming them into cost-equivalent objectives [37] or by viewing them as constraints with lower and higher bounds [38]. However, multi-objective optimization is more realistic because it can explicitly assign an objective function to each sustainability (cost, emissions, jobs, land, social opposition, etc.) criterion without the need for complicated equations. Prior multi-objective studies mostly concentrated on costs and emissions while ignoring the social factors. Ren et al. [39] investigated the operation strategy of a decentralized energy source while balancing energy cost minimization with environmental effect minimizing. Zhang et al. [40] examined the Japanese power generation system from an economic and environmental standpoint. In Taiwan, Ko et al. [41] used a multi-objective optimization to reduce power generating costs and CO_2 emissions. Purwanto et al. [42] created a conceptual framework for a long-term power generating mix in Indonesia that incorporated two goals: lowest generation cost and lowest CO_2 emissions. Mahbub et al. [43] discovered optimal scenarios for addressing the constraints of lowering energy costs and CO_2 emissions in Italy. Pratama et al. [44] assessed different development scenarios for Indonesian electricity production based on economic and environmental trade-offs. Tekiner et al. [45], on the other hand, investigated three goal functions; nevertheless, both non-cost criteria addressed air emissions such as CO_2 and NO_x. There is still the need to develop a multi-objective optimization model for determining trade-offs between several conflicting factors of sustainability. In this study, multi-objective optimization was used to integrate indigenous energy sources to develop a sustainable power generation mix by minimizing power generating costs, minimizing CO_2 emissions, and maximizing the number of jobs created from the construction and operation of power plants.

The Hybrid Structural Interaction Matrix (HSIM), a weighted technique that is ideally suited to dealing with energy decision-making issues, was utilized in this study to calculate the weights of the three objectives to solve the multi-objective power optimization model [46]. The same approach was utilized to analyze the factors contributing to Nigeria's rising demand for electricity.

Nigeria, as one of the top producers of oil and gas all over the world, has an urgent need to develop a long-term plan for its increasing electricity needs [47]. Nigeria also has substantial RE sources. When compared to the 28 TWh produced in 2016 [48], Nigeria's power production in 2021 increased to 36.4 TWh [48]. The industrial sector consumes 94.2% of the nation's electricity, trailed by the residential and commercial sectors, which each consume 4.04 and 1.8% [49].

RE sources such as sun, wind, biomass, and hydro are abundant in Nigeria. Every area of Nigeria receives a lot of solar radiation, with a range of 5,500–6,500 Wh/m^2 [50]. In reality, according to some studies [51,52], solar PV power generation is feasible throughout Nigeria. In the northern regions of the nation, the wind can achieve speeds of up to 7.5 m/s [53]. In terms of biomass production, Nigeria generates 144 million tonnes annually [54]. A total of 277 scattered locations in the nation can produce minor amounts of hydropower [55], and numerous rivers can be dammed to produce huge amounts of hydropower [56]. Despite this, Nigeria's RE resources have not yet been fully exploited.

Nigeria's carbon footprint cannot be underestimated given that they make up about 0.37% of the world's CO_2 emissions in 2020 [57]. In Nigeria's energy sector, CO_2 emissions from power production systems made up around 10.2% of total emissions [58]. Nigerian policymakers are very concerned about reducing GHG emissions from the power industry. Nigeria plans to achieve net zero carbon emissions by 2060 by the President's pronouncement [59]. The power industry can unavoidably be a significant contributor to future carbon emission reduction efforts.

Nigeria now has an unemployment rate of over 33% [60], which is substantially higher than the world average. Due to these alarming numbers, the administration has decided to concentrate on labor indices in any national development programs. One-way power supply systems may be able to meet some of the increasing labor demand is by being able to employ numerous people from the design, development, and operation to decommissioning of Nigeria's power infrastructure.

Studies on sustainable power supply mix in Nigeria are hard to come by, according to the literature review that was conducted. Olusola et al. [61] provided a strategy to electrify Nigeria completely by 2030 that was sustainable, renewable, and economical. In Nigeria, Bello et al. [62] used carbon emission pinch analysis, which includes sector-level macro-planning for energy. Blechinger et al. [63] used energy system simulations and geographic information system tools to develop a least-cost electrification strategy for five states in Nigeria. Ibrahim and Kirkil [64] estimated Nigeria's long-term power supply from 2010 to 2040. Sambo A [65]. used MAED to forecast energy consumption. Audu et al. [66] determined the long-term energy consumption in Nigeria. Amlabu et al. [67] explored four Nigerian regional power supply scenarios. Ezennaya et al. [68] utilized Time Series Analysis to anticipate Nigerian power consumption from 2013 to 2030. Oyelami and Adewumi [69] utilized the Harvey logistic model to forecast Nigerian power investment value from 2005 to 2026. Using LEAP, Emodi et al. [70] evaluated Nigeria's energy circumstance in the following scenarios: baseline, LCM (Low carbon moderate), LCA (Low carbon advanced), and GO (Green Optimistic). Adedokun [71] predicted electricity consumption in Nigeria using the ARIMA model to see how likely it was that Nigeria would be in the top 20 by 2020. To the best of our knowledge, there are no other studies paying attention to Nigeria's electricity generation outlook by addressing economic, environmental, and social objectives.

1.1. Nigerian power sector

Nigeria's growing electricity demand is 80% lower than it should be based on population and income levels [72]. Having a per capita electricity consumption rate that ranks among the world's poorest, there is little or no development in all sectors of the economy; industries are struggling to survive, agriculture is still not commercial, and education and employment are all impacted by the low electricity supply. In developing countries with fewer people, such as Tunisia and South Africa, electricity consumption is 10–30 times Nigeria's. With the COVID-19 pandemic causing major economic setbacks worldwide, Nigeria must urgently address the issue of low electricity supply to compete with its peer countries. Fig. 1 depicts various African countries' per capita power consumption, with Nigeria having the lowest at 137 kWh and South Africa having the highest at 4,944 kWh, Botswana at 1,435 kWh, Zimbabwe at 898 kWh, Namibia at 1,541 kWh, and Libya at 3,871 kWh [73].

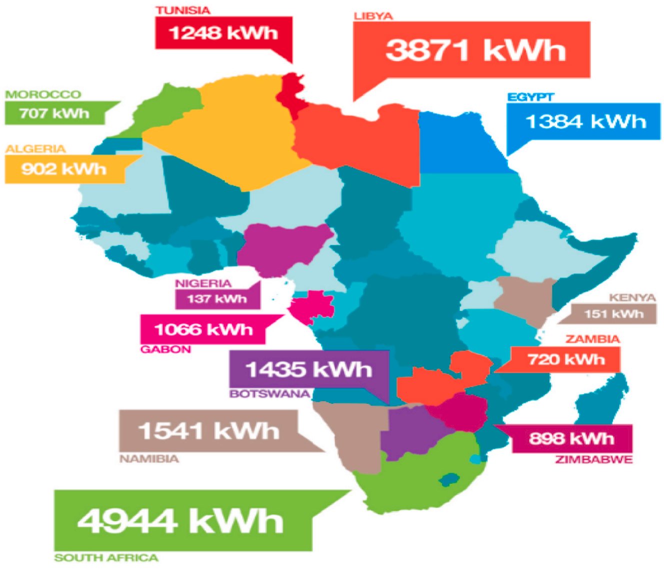

Fig. 1. Selected African countries' per capita power consumption (kWh) [73].

With a growing population, rising income, industrialization, and increased agricultural activity, Nigeria's electricity demand will increase, putting additional pressure on the country's already inadequate electricity supply. Managing the increasing electricity demand is necessary to achieve equilibrium with the power supply.

History of the Nigerian power system dated back to when the Lagos Colony was served by two power plants completed in 1886. The Nigerian Electricity Supply Company (NESCO) was created in 1929, making it the country's first utility corporation [74]. Afterward, in 1951, the Energy Corporation of Nigeria (ECN) was established to supervise electricity transmission and distribution [74], and in 1962, the Niger Dams Authority (NDA) was established [75]. Electricity generation fell under the purview of the NDA, with transmission and distribution falling under the purview of the ECN. It was in 1972 that the ECN and the NDA amalgamated to become the National Electric Power Authority (NEPA), which was later converted into the Power Holding Company of Nigeria (PHCN) in 2005. The distribution section of Nigeria's power supply system has now been completely privatized, resulting in the establishment of Kano, Kaduna, Jos, Eko, Benin, Abuja, Enugu, Port-Harcourt, Yola, Ikeja, and Ibadan Electricity Distribution companies, as depicted in Fig. 2 [76]. Despite the country's lengthy history of electricity reforms, the power industry has developed slowly at most. The on-grid electricity generation in Nigeria is dominated by gas and hydropower, which account for 81% and 19% respectively, of total installed capacity [77]. Fig. 2 depicts the organization of Nigeria's power sector, which is divided into generation, transmission, and distribution [78]. The Nigerian Electricity Supply Industry (NESI) has 22 gas and three hydroelectric on-grid units that can produce 12,522 MW, but the available capacity is only 7,141 MW [79]. Presently, Manitoba (Canada) Hydro International manages the Nigerian Transmission Company. The national grid transmission lines are 330 kV and are about 5,524 km long [80]. Fig. 2 also indicates Nigeria's power distribution system which comprises of 11 power distribution companies. Over 24,000 km of the distribution grid, operating at 33 kV and 11 kV, are in operation [74,78].

The amount of power that can be generated and transmitted is limited by problems associated with the power plants, such as maintenance and repairs. There are also insufficient water supplies, demand imbalances, not enough gas, and line restrictions because of the poor grid infrastructure [81]. Among other things, the mismatch between the growing power demand and supply has resulted to over-reliance on backup diesel generators. Because of these issues, huge sums of money are pumped into the power sector on a daily basis.

For a long time, the government ran and controlled the power sector. There was never enough electricity for the state-owned company, NEPA [82]. Since the democratization of Nigeria in 1999, the Federal Government has invested massively in the power industry, but with little success [82]. Privatization of electricity assets was one of the government's primary reform initiatives [78]. Various policy initiatives were implemented to achieve this goal [74]. The Electric Power Industry Reform Act (ESPR) of 2005 allowed private players into the formerly monopolized sector. Nigeria has a lot of potential for RE. Still, it doesn't have RE-based power plants that generate electricity for the country's grid right now with the exception of hydropower. "Nigeria's solar and wind resources are in abundance based on data from NASA [83], reprocessed by the German Aerospace Center [84], and converted to total load hours by Bogdanov and Breyer [85,86]. However, the Nigerian government's deliberate and supportive policy direction towards a progressive RE master plan is essential [87]. It is anticipated that such a regulatory, legal, and institutional framework would support RE development in Nigeria [78]. The Nigerian government adopted the National Renewable Energy and Efficiency Policy (NREEEP) in 2015. It is the country's first policy for renewable energy and describes how it will be used in the future. By 2030, the government wants to double its on-grid power [80]. In NREEEP 2015, it says that this goal was set when

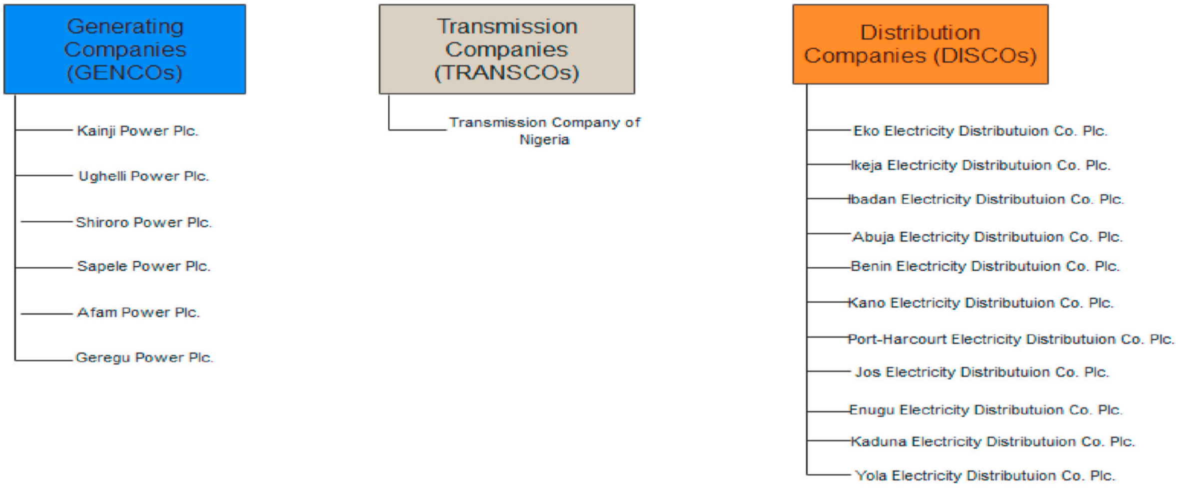

Fig. 2. Overview of the power system chain [88].

the NREAP and NEEAP were made. In the NREEEP 2015 report, on-grid RE supply is expected to grow from 1.3% to 16% in 2030, a significant change. In 2016, the goal was changed to 30% by 2030, all of which have not been achieved" [80].

1.2. Energy sources

Nigeria is deficient when it comes to energy supply, even though it has a lot of fossil fuels and RE sources of its own. Fossil fuels are the country's most utilized source of energy. While RE is unavailable in the power mix of the nation with the exception of hydropower as already stated. The power supply mix comprises 10,142 MW of natural gas (81%). The remainder is hydropower, which accounts for 2,380 MW, or 19% of the total installed capacity [89].

It has been projected that Nigeria's RE potential (hydro, wind, solar, biomass, and geothermal) is above 68,000 MW. The government may have considered this when developing laws to promote RE. In 2005, the government unveiled the Renewable Energy Master Plan (REMP), which aimed to double the country's overall energy production by 2025 through growing renewable energy usage. Short-term: In 2005–2007, the REMP aimed to contribute 13%–23% in the medium term (2008–2015), and 36% in the long term (2016–2025) [89].

On the current assessment, Nigeria's recoverable oil reserves are 28.5 billion barrels, with an average daily output of roughly 2.5 million barrels, including condensates. As exploration and appraisal drilling and deep offshore exploration have continued to accumulate reserves, the average oil depletion rate is just 15%. Over 166 trillion cubic feet (TCF) of Nigeria's gas reserves include associated and non-associated gas. Nigeria is one of the ten nations with the world's largest proven gas reserves.

The Niger Delta has roughly 500 oil fields. The remainder is found on land. In all, 193 of these fields produce oil, while 23 have been shut down [90].

2. Methodology

A sustainable power supply model for Nigeria was developed using multi-objective optimization and is deliberated in this section. This model optimized three competing objectives by minimizing power generating costs, minimizing CO_2 emissions, and maximizing job creation for the developed optimal power supply mix. While the constraints are power demand-supply, power supply resource availability, generation constraint of power plants, budget, and targets of CO_2 emissions. From the base year (2010) to our projected target year (2050), a five-year interval was used to run the optimization model. A summary of the six step methodology was summarized below with Fig. 3 being a schematic representation of the steps that were successively followed for the development of the sustainable power supply mix for Nigeria.

- Step 1: Power system

The Power Energy System (PES) is created in step 1 for modelling purposes which highlights the power supply chain from energy sources to electricity end-users. Nigeria's available energy sources such as diesel, hydro, wind, solar, nuclear, natural gas, etc., are used in different technologies. Concerning power transmission and distribution, distributed technologies generate electricity near load centers, while centralized technologies generate electricity and then being transmitted through power grids.

- Step 2: Power model development

Based on the PES, a long-term power planning model is developed in step 2. To address power supply and sustainability concerns in Nigeria, three objectives were developed: (1) minimization of cost; (2) minimization of CO_2 emissions; (3) and maximization of jobs. Constraints to the optimization model include supply-demand, generation limitations, resource availability, budgetary restrictions, and an emissions target.

- Step 3: Data and assumptions

When running the model, it is necessary to collect the required data, which was done in step 3. For a nation to develop an energy plan, data and assumptions regarding the techno-economic, environment, power demand projection, cost of energy resources, job creation, and statistics on CO_2 emissions used were collected.

- Stage 4: Multi-Criteria Decision Making

This step involves employing the MCDM approach to the three objectives: converting the objectives into a single objective by using a weighted approach to allocate weights to each objective function in the model. The Hybrid Structural Interaction Matrix (HSIM) method was utilized in this step.

- Step 5: Running the developed model

This involves testing the model that was developed using the data obtained in step 3.

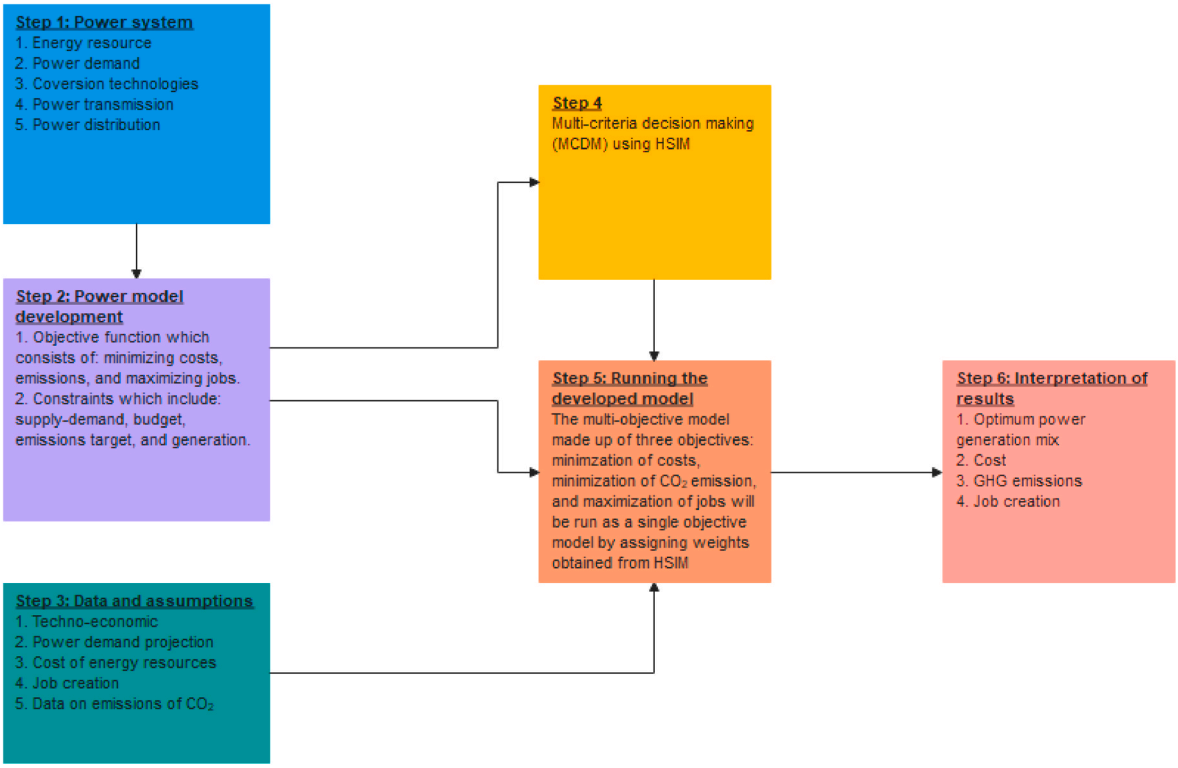

Fig. 3. Schematic representation of the methodology.

- Step 6: Interpretation of results

The optimal power generation mix, CO_2 emissions, cost, and the jobs created from the construction and operation of power plants were then interpreted and analyzed.

2.1. Minimization of power generation costs for the model

The primary priority is to cut electricity generation costs as much as possible (*f1*). In the model, it uses *sLCOE* in Eq. (2) & Eq. (3) to determine *f1* in Eq. (1). *sLCOE* takes into account the costs of building new power plants (*C*), the payback period for old power plants (*O*), the price of fuel (*F*), and other factors. For the cost objective function, the equations look like this:

$$f1=\sum_{t=1}^{T}\sum_{i=1}^{I}\left(1+r^{-t}\right)\left(G_{it}^{new}sLCOE_{it}^{new}+G_{it}^{ext}sLCOE_{it}^{ext}\right) \tag{1}$$

$$sLCOE_{it}^{new}=\left(\frac{\left[C_{it}^{new}CRF_{i}\right]+O_{fix,it}}{8760C_{f,it}}\right)+O_{var,i}+F_{it}\varepsilon_{it} \tag{2}$$

$$sLCOE_{it}^{ext}=\frac{O_{fixed,it}}{8760C_{f,it}}+O_{var,it}+F_{it}\varepsilon_{it} \tag{3}$$

$$CRF_{i}=\frac{r(1+r)^{n}}{(1+r)^{n}-1} \tag{4}$$

The decision variables in the model are *CRF* for cost recovery factor in Eq. (4), C_f for capacity factor, ε for efficiency of transforming heat into electricity, r for the discounted rate, and t for year. The relationship between installed capacity and capital expenditures for a certain year horizon is an input parameter to a learning curve model. According to a cumulative installed capacity prediction, the amount of capital investment may be estimated:

$$C_t=C_o\cdot N_t^{\varnothing} \tag{5}$$

$$1-2^{\varnothing} \tag{6}$$

Eq. (6), which signifies the rate of technical learning, C_t in Eq. (5) is the decrease in future capital expenditures as a percentage that occurs with each capacity doubling up (N_t). How quickly individuals learn is determined by the progress ratio. The capital expenditure in the base year is denoted by the symbol C_o (2010).

2.2. The reduction of CO_2 emissions from power production facilities

It is also an objective to reduce CO_2 emissions (*f2*) represented by Eq. (7) during the lifecycle of the energy-generating technology. The CO_2 life cycle emissions of each power plant are determined by the CO_2 emission factor (E) being multiplied by the quantity of energy that is produced by the power plant:

$$f2=\sum_{t=1}^{T}\sum_{i=1}^{I}CO_2emissionfactor_{it}\cdot G_{it} \tag{7}$$

2.3. Maximization of job opportunities

The job objective function (*f3*) maximizes total job years, as its socially more acceptable to have higher employment rates than lower rates. Eq. (8) represents the whole job objective function. The job creation objective function *f3* was obtained by multiplying the amount of power produced by the construction and operation job creation factors of each technology.

$$f3=\sum_{t=1}^{T}\sum_{i=1}^{I}(b_i+h_i)G_{it}^{new}+\sum_{t=1}^{T}\sum_{i=1}^{I}h_iG_{it}^{ext} \tag{8}$$

2.4. Multi-objective function

The optimal power generation mix was obtained as a result of optimizing the three objectives considered in this study as represented by the multi-objective model in Eq. (9) [91]. The objective function is expressed as follows:

$$f4 = w1\cdot f1 + w2\cdot f2 + w3\cdot f3 \tag{9}$$

Where $w1$, $w2$, and $w3$ are the weighted factors of $f1$, $f2$, and $f3$. The optimization model in this situation is constrained by five constraints, which are mentioned in the next section.

2.5. Constraints for the developed model

This section summarizes the restrictions taken into consideration in the model. In the following section, the model's resilience needs are met by constraints.

2.5.1. Power demand-supply constraint

The overall amount of energy produced by all kinds of power plants should be sufficient to fulfill the whole amount of electricity required in a given year horizon. This is represented by Eq. (10):

$$\sum_{i=1}^{I}\left(G_{it}^{new} + G_{it}^{ext}\right) \geq D_t \tag{10}$$

where D_t denotes the demand for electricity in the year t.

2.5.2. Power supply resource availability

For year t, the amounts of fossil fuel used by power generation systems must not exceed the maximum amount of fossil fuel generated by the relevant fuel type and allotted to power generation technologies for the same year which is depicted in Eq. (11).

$$\sum_{i=1}^{I} G_{it}^{new}\cdot\varepsilon_{it} + \sum_{i=1}^{I} G_{it}^{ext}\cdot\varepsilon_{it} \leq F_{sit} \tag{11}$$

It was decided to add the RE penetration constraint into the model to guarantee that the RE objectives are met on a period-by-period basis. By the study, the RE objectives were established at 20, 35, and 50% for the years 2030, 2040, and 2050.

$$\frac{\sum_{i=2}^{9}\left(G_{it}^{ext} + G_{it}^{new}\right)\cdot 8760C_{fi}}{\sum_{i=1}^{I}\left(G_{it}^{ext} + G_{it}^{new}\right)\cdot 8760C_{fi}} \geq RENTargets \tag{12}$$

2.5.3. Generation constraint of power plants

Restrictions on electricity generation are related to the use of current and additional capacity and the proportion of various technologies in an overall power generation system.

$$X_{it}^{new} = 8760(1-\rho)C_{fi}G_{it}^{new} \tag{13}$$

$$X_{it}^{ext} \leq 8760(1-\rho)C_{fi}G_{it}^{ext} \tag{14}$$

$$X \leq \omega_{it}\left(X_{it}^{new} + X_{it}^{ext}\right) \tag{15}$$

Each newly installed technology's annual net power generation is estimated using Eq. (13). Eq. (14) determines the maximum amount of power that may be produced from the current capacity in a given year. To avoid the excessive generation of any power technology, Eq. (15) mandates that each technology may only generate a specified fraction of the total yearly power generation.

2.5.4. Budget constraint

Budget constraints are imposed on capital expenditures because the capital expenses of constructing new infrastructures are relatively high.

$$\sum_{i=1}^{I}\frac{r(1+r)^{CT_i}}{(1+r)^{CT_i}-1}\cdot INVC_{it}\cdot NAC_{it} \leq bgC \tag{16}$$

In Eq. (16), the annual investment cost of developing power plants is restricted to a specific upper limit.

2.5.5. Targets of CO_2 emissions

The carbon emissions reduction objective also served as a constraint, with the total quantity of CO_{2eq} emissions being limited to a maximum as highlighted in Eq. (17):

$$\sum_{i=1}^{I}\left(\left(G_{it}^{ext} + G_{it}^{new}\right)\cdot 8760C_{fi}\cdot CO_2emissionfactor_i\right) \leq CO_2emission\ target \tag{17}$$

3. Study and data assumptions

Existing techno-economic, environmental, power demand projection, cost of energy sources, job creation, and CO_2 emissions data for the Nigerian power system was obtained from various literature to demonstrate the multi-objective model's application. The base year is 2010 and the forecast period is for 40 years, the projection started from 2011 to 2050 with an interval of 5 years.

The assessment of power demand in on-grid and off-grid systems can either be done as a combined demand or as separate demands, depending on the methodology that is used. Examples include a study conducted by the (Energy Commission of Nigeria) ECN on the energy implications of Nigeria's Vision 2020. Such that the Model for Analysis of Energy Demand (MAED) was used to project that Nigeria's total electricity demand (combined on-grid and off-grid) by 2030 will be approximately 668.75, 1138.20, 1,343.22, and 1,821.80 TWh depending on the reference, high growth, optimistic I, and optimistic II scenarios, respectively [92]. In a separate piece of study, the Multi-tier framework for electricity access that was developed by the World Bank was utilized to estimate that Nigeria's on-grid electricity demand by 2030 will be approximately 59.3, 64.3, and 74.2 TWh, respectively, for business-as-usual, moderate, and green transition scenarios. This estimate was made using the Multi-tier framework for electricity access. According to the findings of the study, the power consumption off-grid in the year 2030 would be around 143.4, 135.6, and 130.8 TWh for the three similar scenarios [93], with the maximum demand being approximately 143.4 TWh.

3.1. Power conversion data

Nuclear power plants, gas turbines, biomass, large and small hydropower plants, wind turbines, geothermal, solar thermal, and solar photovoltaic power plants, etc., are among the power conversion technologies considered in this study. The features of each technology are summarized in Table 1, which includes cost variables, technical information, and capacity limits. For most technologies, the techno-economic characteristics are considered to remain constant across the whole analytical horizon. When the learning rate is taken into account, however, it is expected that the investment cost for certain renewable technologies would fall. The growing capacity limitation for each phase is partly alleviated as the planning horizon approaches its end. The total number of direct, indirect, and induced full-time-equivalent (FTE) employment produced by each technology in each phase is shown in Table 2. Table 3 shows the CO_2 emission factors resulting from fossil fuel combustion.

3.2. HSIM ranking

The HSIM approach is one of the strategies that may be used for making decisions with many objectives and doing analyses. Within the context of this study, HSIM was utilized to ascertain the relative importance of factors such as cost, CO_2 emissions, and job creation. According to HSIM, a particular element pair may interact with one another in several distinct ways. On the other hand, only an interaction that is founded on a particular contextual relationship applies to the situation that is currently taking place. In most cases, consideration is given to the orientations of the components that affect a system while

Table 1
Power generation systems' technical and economic characteristics [95–106].

Technology	Construction time (year)	Lifetime (year)	Capacity factor (%)	Self-consumption (%)	power capacity (GW)	Efficiency (%)	Capital cost ($/kW)	Fixed O & M cost ($/kW)	Variable O & M cost ($/kW)
Steam PP	5	30	70	6.8	3750	38	900	9500	0.48
Combined Con	5	35	70	1.9	–	32	700	4400	0.42
Combined Adv	5	35	80	1.9	–	47	1140	21000	2.6
Gas Turbine Conv	2	12	60	0.8	5000	34	550	4500	0.6
Gas Turbine Adv	3	15	60	0.8	846	40	780	24000	4.3
Coal Conv	3	30	75	5.5	–	35	1600	64000	–
Coal Adv	4	50	80	6.5	–	34	2200	88000	–
IGCC	4	40	80	10	–	45	3700	92000	6.5
Diesel engine	1	14	70	6.5	25000	40	550	3800	0.75
Nuclear Conv	7	45	80	10	–	32	4000	74000	0.7
Nuclear Adv	8	60	85	8	–	33	4200	69000	0.5
Hydro Large	7	45	18	0.5	1940	100	1200	10800	–
Hydro Small	4	40	35	0.5	64	100	2000	14000	–
Fuel Cell	0	5	60	–	–	47	4460	40000	–
Wind Turbine	2	25	30	1.4	–	100	1400	48000	–
Solar PV	1	30	18	–	400	100	1200	24000	–
Solar thermal	2	35	38	–	–	100	4300	64000	–
Geothermal PP	7	30	8	8	–	100	5800	84000	1.1
Landfill	2	20	70	3	–	30	3300	2000	1.7
Incinerator	3	30	75	5	–	31	6400	64000	–
Solar PV (DG)	0	30	17	–	–	100	1500	37000	–
Gas Engine	1	3	90	0.7	5500	26	770	8000	5.1

Table 2
Effective factors in the development of jobs in the power generating industry [107].

Power technology	Technology construction stage (GWh)	Technology operation stage (GWh)
Steam PP	0.82	0.15
Combined Con	0.16	0.32
Combined Adv	0.31	0.35
Gas Turbine Conv	0.83	0.64
Gas Turbine Adv	1.07	1.07
Coal Conv	0.73	1.31
Coal Adv	0.08	0.26
IGCC	0.26	0.20
Diesel engine	0.16	0.32
Nuclear Conv	0.26	0.20
Nuclear Adv	0.20	0.26
Hydro Large	0.20	0.82
Hydro Small	0.20	0.82
Fuel Cell	0.10	0.11
Wind Turbine	0.3	0.08
Solar PV	0.06	0.83
Solar thermal	1.10	1.70
Geothermal PP	0.05	0.51
Landfill	0.13	0.73
Incinerator	0.13	0.73
Solar PV (DG)	0.60	0.83
Gas Engine	0,03	0.16

Table 3
Factors affecting CO_2 emissions and fuel costs [108,109].

Technology	Fuel price (Cent/MJ)	CO2 emission (kg/GJ)
Gas	0.41	56.2
Coal	0.22	95.6
Oil	0.53	77.6
Diesel	0.92	74.4

making contextual linkages.

As a consequence of this, the HSIM model is intrinsically intertwined with the concept of orientation and direction. As a result of this, if $e_{ij} = 1$, then $e_{ji} = 0$, which indicates that transitivity exists. Because of this, it will be impossible for components *i* and *j* to successfully interact with one another if elements *j* and *i* interact effectively [94].

This is mathematically stated in Eq. (18) as:

$$e_{ij} = \begin{cases} 1 & \text{if } i \text{ depends on activity } j, \\ 0 & \text{if } i \text{ does not depend on activity } j, \end{cases} \tag{18}$$

The technique for establishing the HSIM for a given set of variables is

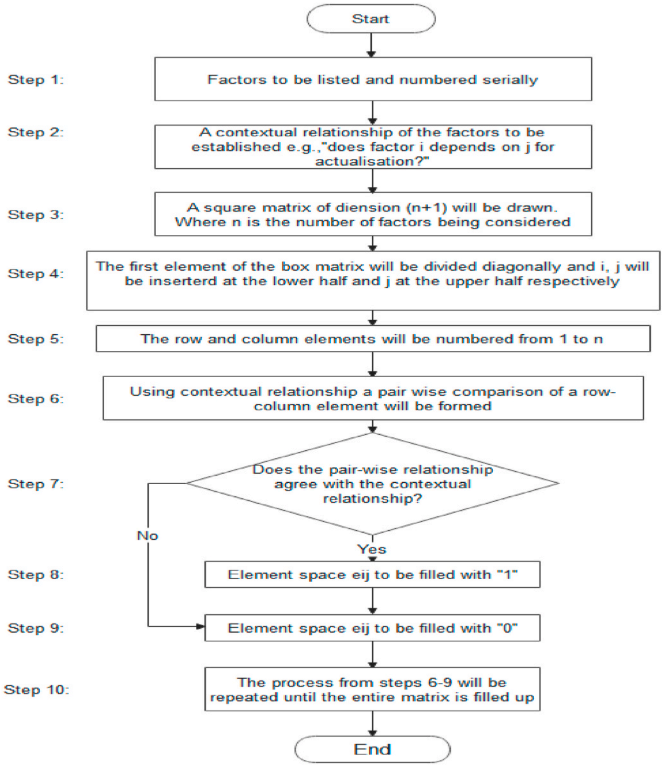

Fig. 4. Diagram of the HSIM development process [94].

represented in Fig. 4 in a step-by-step manner and HSIM in Table 4.

The models used for calculating the weights of the objectives are highlighted in Eq. (19), Eq. (20), Eq. (21), and Eq. (22):

$$I_{RFi} = \left\{ \frac{N_{SFi}}{T_{NF}} x M_{SR} \right\} + \left\{ \frac{b}{T_{NF}} (M_{SR} - C) \right\} \tag{19}$$

$$c = \frac{M_{PSF}}{T_{NF}} x M_{SR} \qquad 20$$

$$b = N_{SFi} + 1 \tag{21}$$

$$N_{wi} = \frac{x_i^{1/n}}{\sum_{i=1}^{n} x_i^{1/n}} \tag{22}$$

"where I_{RFi} is the intensity of factor i's significance rating, N_{SFi} is the number of subordinate factors to particular factor *i*, M_{PSF} is the most number of subordinate elements that can be considered, C constant, $b = T_{NF}$ the proportion of variations, T_{NF} is the number of variables in total, M_{SR} the highest possible scale rating, N_{wi} is the factor's normalized weight *i*, N number of variables, and x_i is the original rate of factor *i* before normalization." [46].

Table 5 displays the weights of each of the objectives considered in this study and their degree of importance. The scale rating was between 0 and 9, with 0 being the lowest possible score and 9 representing the greatest possible score [110]. The number of subordinate factors that may be accessed by a component is what ultimately decides the principle that will be used to weigh or give a degree of importance to those elements. As a result, the values were found to be appropriate for the weights of cost, CO_2, and job's objective functions which are 0.330, 0.340, and 0.330, respectively.

4. Results and discussion

The planning for Nigeria's sustainable power supply was carried out with consideration given to the following three objectives: reducing costs, reducing CO_2 emissions, and increasing jobs. The model was solved by utilizing a modelling program called GAMS (General Algebraic Modelling System).

4.1. Demand for electricity in Nigeria

Electricity demand in Nigeria from the household, service, industrial, transportation, and agricultural sectors in the base year is 187 TWh which is projected to be 299 TWh in 2020 [111]. Fig. 5 depicts how the electricity demand will attain 2,003 TWh by 2050. Among the electricity demand sectors, the household sector has the highest demand which will increase from 71 TWh in 2010 to 1,218 TWh by 2050. This is followed by the service, industrial, and transportation sectors.

4.2. Results obtained from the simulation

4.2.1. Power generation by technologies

The optimum trajectory of Nigeria's overall power generation is represented in Fig. 6. From the base year to 2050, the projected power supply increased from around 218 TWh to about 2,100 TWh. The Hydropower large power plant and solar PV aggressively penetrated the power supply mix over the projected period.

Table 4
HSIM demonstrating the pair-wise connection between cost, CO2, emissions, and jobs.

i	*j* *Cost*	*CO₂*	*Jobs*
Cost	0	1	0
CO₂	0	0	0
Jobs	1	1	0

Table 5
Normalized weights of cost, CO2, emissions, and jobs.

Element number	C	I_{RFi}	$\frac{1}{n}x_i$	N_{wi}
Cost	6	5.000	1.080	0.330
CO₂	6	9.000	1.110	0.340
Jobs	6	5.000	1.080	0.330
		Total	3.270	1.000

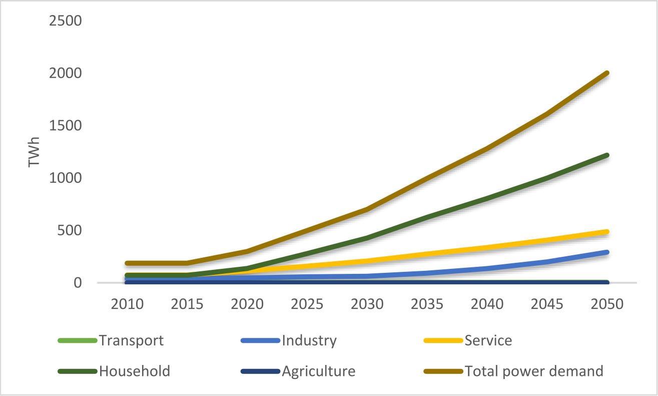

Fig. 5. Nigeria's electricity demand from 2010-to 2050 [111].

The base year of 2010 in the power supply mix is made up of 10% Gas Turbine Conventional, 5% Diesel engine, 6% Hydropower large, and 79% Gas engine. Fossil fuels dominate the power generation mix in the base year which accounts for 94% and renewable energy is 6%. By the year 2050, renewable energy will largely be integrated into the power supply mix which will be made up of 23% Combined advanced, 11% Gas turbine conventional, 3% Gas Turbine advanced, 8% Nuclear advanced, 12% Hydropower large, 1% Hydropower small, 2% Wind turbine, 15% solar PV, 12% Solar thermal, 7% Incinerator, and 6% Gas engine. Renewable energy sources will make up at least 49% of the power supply mix, nuclear energy which is mostly classified as an alternative energy source is 8%, and the remaining 48% is for fossil fuels. Renewable energy sources massively increased by about 716% in the power generation mix from the base year to the projected period (2050). Gas power plants remain heavily in the power supply mix because of the low price of natural gas. Considering the environmental impact of coal which is often at times referred to as the dirtiest form of fossil fuels and the need to adhere to emission regulations, coal power plants are unavailable in the power supply mix. In addition, steam power plants have been eliminated during the planning period. While gas power plants have been considerably present during the planning period because of the low cost of gas but have still been significantly reduced during the planning horizon.

4.2.2. Emissions from the power supply mix

The sole GHG that was taken into consideration in this study was CO_2 emissions since it is the most prevalent GHG in the energy sector. The pattern of emissions that are expected to take place between the base year and 2050 is shown graphically in Fig. 7. According to the study, there has been an ongoing increase in CO_2 emissions of varying magnitudes. The emissions of CO_2 will increase from 111 million tonnes of CO_2 (M_tCO_2) in the base year to about 266 M_tCO_2 in the year 2050. The result shows significant dependency on technologies that rely on fossil fuels for the generation of electricity, this is mostly attributable to the cheaper cost of natural gas; this dependence has led to the development and rise of CO_2 emissions. The CO_2 emissions rapidly increased at first, but then leveled off and remained constant from 2030 to 2045, and then

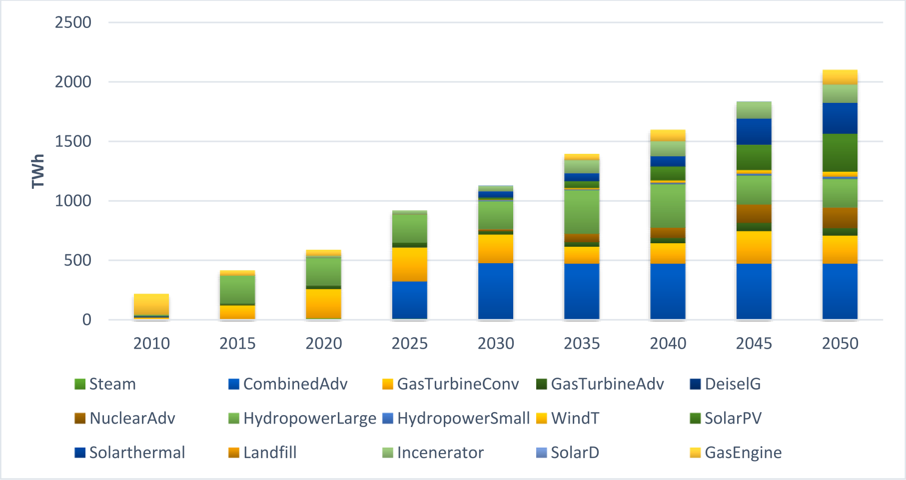

Fig. 6. Nigeria's electricity supply projection from 2010 to 2050.

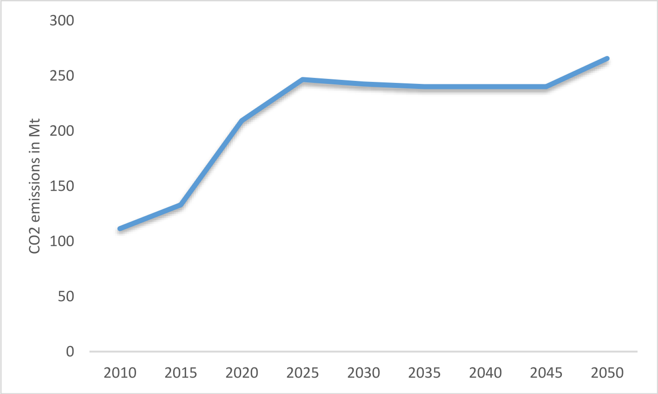

Fig. 7. Nigeria's CO_2 emissions from power generation.

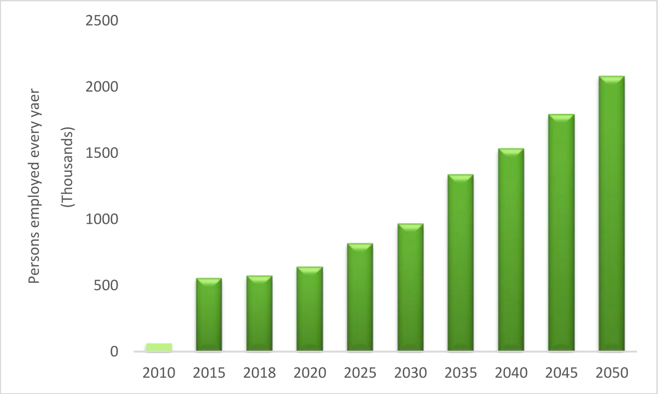

Fig. 8. Persons employed from PP construction and operation 2010–2050.

gradually reached the peak level of 266 M_tCO_2 in 2050.

A more aggressive penetration of renewable energy sources will go a long way toward helping Nigeria decrease its national GHG emissions inventory and supporting the country's efforts toward reaching a variety of international climate commitments. There is an urgent requirement for concerted efforts to accelerate the deployment of renewable energy technology across the nation. Therefore, obstacles that are responsible for the slow transition to renewable energy sources such as the absence of incentives, subsidies, grants, scarcity of renewable energy technologies experts, inadequate research and development capabilities, government bureaucracy, etc., need to be minimized or even eliminated for the transition to occur.

4.2.3. Jobs created

The employment impact of the power generation planning is displayed in Fig. 8. The capacity to generate power expanded by around 865% throughout the planned period, and the number of jobs that were created increased by more than 3,068%. This indicates that a 1% increase in power generation will result in a 3.54% rise in the number of jobs created. The overall number of jobs in the base year was approximately 66 thousand, but that number is projected to rise to 963 thousand by 2030 and peaked at almost 2.05 million jobs by 2050. This implies that there is great potential for job creation if power generation is expanded to harness all the available energy sources in Nigeria including fossil fuels, renewable energy, and alternative energy. Even though this study only considered jobs that will be created from the construction and operation of power generation technologies, there is much more room for job creation if the manufacturing of parts for the power plants is considered together with decommissioning jobs. As a consequence of this, the potential for employment in Nigeria will increase significantly if these are included. The preceding information indicates that a shift in strategy toward the incorporation of renewable energy sources into the power generating process has the ability not only to industrialize the economy but also to bring down the extremely high unemployment rate that exists in the country.

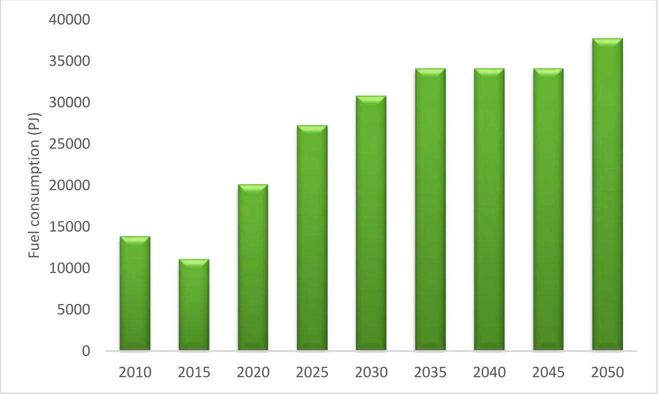

Fig. 9. Fuel consumed for power generation.

4.2.4. *Power generation fuel consumption*

As can be seen in Fig. 9, the total amount of fuel that was used for the production of electricity in the base year was 13,814 PJ. The fuel consumption as projected from the base year increased and stabilized at 34,074 PJ from 2035 until 2045 when consumption of fuel remained constant. The fuel consumed for power generation during the study period peaked at 37,694 PJ in 2050 which might be ascribed to the rapid integration of various sources of energy to satisfy the growing electricity demand. The amount of fuel used had increased by a staggering 146% between the years 2011 and 2035, and by 11% between 2035 and 2050. As highlighted earlier, there is an aggressive integration of energy sources throughout the power planning horizon, this is because of the growing electricity demand. As Nigeria is a developing nation factors such as industrialization, GDP growth, income growth, population growth, literacy, urbanization, etc., are driving factors for the increment of electricity demand [63].

4.2.5. *Costs of implementing the power supply system*

Fig. 10 displays the costs of power generation throughout the planning period. These costs are comprised of constant O&M expenses, variable O&M costs, and capital costs. The results demonstrate a rising expansion of annual investments throughout the energy planning horizon. The costs of generating in the base year are as follows: fixed O&M costs amount to 24.5 billion US$; variable O&M costs amount to 7.2 billion US$; and capital costs total 900 million US$. The whole cost of producing electricity is projected to drop to roughly 27.1 billion US$ by the year 2050. The enormous expenditures made on new power production facilities led to the power generation capital cost reaching its all-time high of 45 billion US$ in the year 2020. The rapid rise in capital costs can be attributed to the investments made in expanding hydropower large plants, incinerator power plants, and gas turbine conversion facilities. In 2020, the fixed costs reached their maximum level of 36 billion US$. The cost of overall generating was at its highest in the year 2030, coming in at 13.4 billion US$. This can be attributed to the decreased costs of operation, maintenance, and fuel that have resulted from the introduction of solar power generation plants and wind turbines, as well as the expansion of hydropower plants and the construction of small hydropower plants and incinerator power plants, among other types of power plants. The significant decrease in the prices of producing electricity as a result of the widespread adoption of renewable energy technology is the most significant benefit that conventional energy sources do not offer in comparison to renewable energy sources. On the other hand, this does not necessarily imply that the initial capital investment required for renewable energy technology is less than that required for conventional technologies. It is important to make it clear that these costs are only associated with the energy system when they are considered in isolation, and that they do not represent the total net cost to the nation. When all opportunities are considered together, an energy system with a high proportion of renewable power will have the lowest overall cost. When viewed from an economic perspective, the total annual cost of an energy system that is 100% sustainable will, over time, be lower. During the transition period, there will be an increase in capital expenditures, but the cost of gasoline will continue to go down. This will result in energy independence as well as energy security for Nigeria given that the country's energy system will mostly be based on local solar, hydro, biomass, and wind resources.

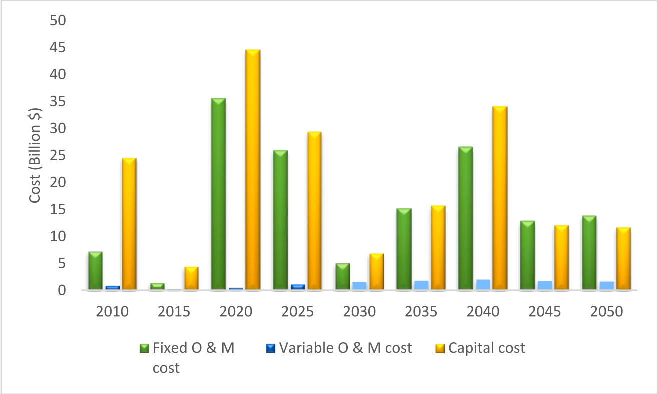

Fig. 10. Power generation costs.

4.3. *Comparison of results and outlook*

In this part of the study, to obtain a more comprehensive understanding of power planning in Nigeria, relevant papers were compared with the findings of this study. An investigation was carried out to determine whether or not it is possible to run a power supply system entirely on renewable sources of energy in Nigeria. The findings of this study are consistent with the outcomes of the Renewable Energy Scenario (REN) 1, including the amount of CO_2 emissions, the number of jobs produced, and the power supply mix [111]. After reaching a peak of approximately 280 M_tCO_2 in 2040, the REN1 scenario's CO_2 emissions began a steady fall that eventually brought them to levels very close to zero. As a result of the fact that the REN1 scenario was built on the premise of reaching a power supply mix consisting of 100% renewable energy by the year 2050, fossil fuel power plants were fully eliminated from the power mix to accomplish this goal. On the other hand, the purpose of this study is to figure out how to get the best possible combination of sources of power while minimizing wasteful spending and emissions of greenhouse gases and boosting employment opportunities. Therefore, fossil fuel power plants continued to be a part of the mix of power supplies, which is responsible for the rise in CO_2 emissions from 240 M_tCO_2 in the year 2040 to 266 M_tCO_2 by the year 2050, instead of decreasing to zero as predicted by the research that was compared.

The LEAP energy modelling tool was utilized by Emodi et al. [70] to devise a low carbon emission energy development plan for Nigeria from the years 2010–2040. According to the research, the reference scenario predicts that the energy demand will rise to 3,075 PJ by 2040, with a corresponding increase in greenhouse gas emissions of 201.2 Mt CO2. In the GO scenario, more aggressive policy action by the Nigerian government would lead to a drop in both energy demand (2,249 PJ) and GHG emission (124.4 M_tCO_2) in the year 2040. The demand for energy and GHG emission substantially dropped by the year 2040 because of energy efficiency and conservation measures being implemented in the GO scenario. Emodi et al. [70] obtained that CO_2 emissions will attain 240 M_tCO_2 by the year 2040, which is obviously in line with our findings. Because of the larger participation of fossil fuel plants in the energy mix throughout the planning era, the energy demand is significantly higher in this location.

According to the results of the studies reviewed, Nigeria holds the potential to meet its energy needs and minimize its emissions of GHG by using energy sources that are available to the nation. As a consequence of this, it is necessary to work as swiftly as possible toward the goal of integrating all of these energy sources to form an optimal power supply mix. Most significantly, it was obtained that massive hydropower plants and solar PV will be the dominating technologies for power supply over the planned timeframe. As a consequence of this, the Federal Government of Nigeria (FGN) has to position solar PV, which are also known as solar cells, at the core of its policies addressing the distribution of electricity. Within a short period, the FGN has to initiate policies and regulatory frameworks that can advance solar PV technologies as well as other RE technologies across the nation. Even if there have been some efforts made in this respect, such as the introduction of feed-in tariffs and the decrease of import duties on RE Technologies, the FGN has to establish new policies to speed up the distribution of RE Technologies across the country. A future goal policy ought to be the adoption of a RE portfolio standard. This standard ought to make it obligatory for all power producers and distributors, respectively, to create energy from renewable sources and to acquire electricity from businesses that generate electricity using renewable sources. The nationwide shift to the use of renewable energy sources will be accelerated as a result of the execution of this initiative. The two recognized and most feasible RE Technologies (solar PV and hydropower large plants) are plagued by the variability of supply, and this will become a hindrance to the transition to total renewables if it is not addressed. As a result of this, technologies for the storage of power, such as batteries and pumped hydro, will be necessary to offer flexibility within the system and ensure that the quantity of energy demand is always equal to the amount that is supplied.

5. Conclusion

Energy accessibility and security as well as the mitigation of climate change at a cost that is affordable are the modern focal points of studies for economies that are still in the process of developing or underdevelopment all over the world. The three goals that were addressed in this research all have a significant connection to the use of renewable energy sources (minimization of costs, minimization of CO_2 emissions, and maximization of jobs). In the course of this study, an effort was made to investigate the best possible power supply mix by utilizing the GAMS model. This was done to reduce costs and emissions and increase job opportunities. According to the findings, Nigeria would have the capability to generate 2,100 TWh of power by the year 2050. In addition, solar PV and hydropower large would account for the majority of Nigeria's long-term energy mix during the period that was forecast. In addition, by the year 2050, the power supply mix will include the generation of electricity from solar thermal plants, incinerators, nuclear power plants, gas plants, combined plants, and diesel engines. It was found that the construction and operation of power generation plants will contribute around 2.05 million jobs to the economy by the year 2050. These positions will be created over the next three decades. By the year 2050, CO_2 emissions will have attained 266 M_tCO_2. The cost of producing electricity is projected to go down from its peak of 36 billion US dollars in 2030 to 27.1 billion US$ in 2050. It was found feasible to satisfy Nigeria's ever-increasing demand for electricity by tapping into indigenous energy sources. It was also obtained from the results, that it is feasible for Nigeria's economy to keep up with the nation's growing demand for power despite the country's relatively high power system costs. Although there are many advantages to a sustainable power supply system, an active and passionate governmental intervention would be necessary to propel the development of renewable energy technology in Nigeria. This is the case even though there are many benefits to such a system. To make renewable energy sources more competitive, it is necessary to remove the obstacles that are causing the slow transition to these sources. These obstacles include fossil fuel subsidies and grants, inadequate infrastructure, inadequate training of personnel, lack of public awareness, and so on.

The lack of data and the significant assumptions that were formed in the course of this study were the two primary obstacles that stood in the way of significant progress being accomplished. The projection of future prices of natural gas, diesel, coal, and oil will be extremely difficult to get right because of the unpredictability of a variety of factors, such as fuel prices. The nations that make up the (Organization for Economic Co-operation and Development) OECD have contributed towards the development and operation of power plants in underdeveloped and developing economies. As a consequence of this, the results will not be precise, and one must use some degree of discretion while interpreting and analyzing the results. Despite this, it is felt that the findings provide an excellent basis for addressing the issues with Nigeria's electricity supply and reducing the emissions of GHG's. This research will be expanded in the future to include developing several scenarios and comparing the results of those scenarios, in addition to investigating several additional competing objectives for the optimization model.

Credit author statement

Hanif Auwal Ibrahim: Conceptualization, Methodology, Software, Writing-Original draft preparation, Writing-Reviewing and Editing. Michael Kweneojo Ayomoh: Supervision, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge supplementary support from the Climate Compatible Growth Program (CCG) of the UK's Foreign Development and Commonwealth Office (FCDO). The views expressed in this paper do not necessarily reflect the UK government's official policies.

The authors would also like to acknowledge Dr. Mohammad Saeid Atabaki of Department of Industrial Engineering, Faculty of Engineering, Kharazmi University, Tehran, Iran for his guidance on using the General Algebraic Modelling System (GAMS) tool.

How this study maps U4RIA goals

The basic values of U4RIA, namely Ubuntu, retrievability, reusability, repeatability, reconstructability, interoperability, and auditability, were incorporated into this research. The Ubuntu concept was instilled via the collaboration of numerous partners. The demand for community engagement spanning indigenous societal members, academia, government agencies, business practitioners, medical experts, legal practitioners, and others in the identification and prioritization of driving factors for energy mix in power generation led to the creation and description of Ubuntu in U4RIA. Ubuntu is significantly linked in this study to the interactive synergy among people of various backgrounds for the sake of achieving a cooperative goal. The simplicity with which sourced data and information that formed the primary motive for energy mix for sustainable power supply for Nigeria may be tracked was the subject of this research. This is expected to become increasingly essential as the push for decarbonization, green energy, and mixed renewable energy sources becomes completely entrenched as energy policy in various African and developing countries in the not-too-distant future. Links, websites, journals, conferences, webinars, videos, and audio sources of information have all been gathered and saved for convenient access.

Reusability was considered in this study under two headings: reusability of resource materials and reusability of the documentation in the article, both of which are important for future energy policy in Nigeria. The resource materials' reusability is enabled by their retrievability, while the study paper's reusability to lead the design of sustainable green energy policy in emerging economies is facilitated by transparency in the documentation. The adaptability of the suggested paradigm reinforces U4RIA's repeatability component. In this study, the term reconstructability was attained using the notion of systematic traceability for prospective improvement. The proposed multi-objective energy mix model incorporated this. To satisfy a given purpose, the model can be extended or reduced in all of its portions. System thinking was used to create interoperability.

References

[1] Shari Babajide Epe, Dioha Michael O, Abraham-Dukuma Magnus C, Sobanke Victor O, Emodi Nnaemeka V, Clean cooking energy transition in Nigeria: Policy implications for Developing countries, Journal of Policy Modeling 44 (2) (2022) 319–343, https://doi.org/10.1016/j.jpolmod.2022.03.004.

[2] N. Ye, T. Kueh, L. Hou, Y. Liu, H. Yu, A bibliometric analysis of corporate social responsibility in sustainable development, J. Clean. Prod. 272 (2020), 122679, https://doi.org/10.1016/j.jclepro.2020.122679.

[3] World Bank, Nigeria's Economy Faces Worst Recession in Four Decades, Says New World Bank Report, The World Bank, 2020. https://www.worldbank.org/en/news/press-release/2020/06/25/nigerias-economy-faces-worst-recession-in-four-decades-says-new-world-bank-report. (Accessed 29 July 2022).

[4] O. Olujobi, D. Ufua, M. Olokundun, O. Olujobi, Conversion of organic wastes to electricity in Nigeria: legal perspective on the challenges and prospects, Int. J. Environ. Sci. Technol. 19 (2) (2021) 939–950, https://doi.org/10.1007/s13762-020-03059-3.

[5] O. Iroh, I. Kalu, A. Nteegah, Empirical cost of electricity outage on labour and capital productivity in Nigeria, Appl. J. Econ. Manag. Soc. Sci. 3 (1) (2022), https://doi.org/10.53790/ajmss.v3i1.23.

[6] World Bank, in: Access to electricity (% of the population) - Nigeria | Data, 2022. Available from, https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NG. (Accessed 28 March 2022).

[7] X. Zhao, M. Mahendru, X. Ma, A. Rao, Y. Shang, Impacts of environmental regulations on green economic growth in China: new guidelines regarding renewable energy and energy efficiency, Renew. Energy 187 (2022) 728–742, https://doi.org/10.1016/j.renene.2022.01.076.

[8] J. Walther, M. Weigold, A systematic review on predicting and forecasting the electrical energy consumption in the manufacturing industry, Energies 14 (4) (2021) 968, https://doi.org/10.3390/en14040968.

[9] C. Berglund, P. Söderholm, Modeling technical change in energy system analysis: analyzing the introduction of learning-by-doing in bottom-up energy models, Energy Pol. 34 (12) (2006) 1344–1356, https://doi.org/10.1016/j.enpol.2004.09.002.

[10] R.G. Cong, An optimization model for renewable energy generation and its application in China: a perspective of maximum utilization, Renew. Sustain. Energy Rev. 17 (Jan. 2013) 94–103, https://doi.org/10.1016/j.rser.2012.09.005.

[11] K.U. Rao, V.V.N. Kishore, A review of technology diffusion models with special reference to renewable energy technologies, Renew. Sustain. Energy Rev. 14 (3) (Apr. 2010) 1070–1078, https://doi.org/10.1016/j.rser.2009.11.007.

[12] P.D. Lund, Energy policy planning near grid parity using a price-driven technology penetration model, Technol. Forecast. Soc. Change 90 (PB) (Jan. 2015) 389–399, https://doi.org/10.1016/j.techfore.2014.05.004.

[13] P. Lund, Market penetration rates of new energy technologies, Energy Pol. 34 (17) (Nov. 2006) 3317–3326, https://doi.org/10.1016/j.enpol.2005.07.002.

[14] S. Mallah, N.K. Bansal, Renewable energy for sustainable electrical energy system in India, Energy Pol. 38 (8) (Aug. 2010) 3933–3942, https://doi.org/10.1016/j.enpol.2010.03.017.

[15] N.A. Utama, K.N. Ishihara, T. Tezuka, N.A. Utama, K.N. Ishihara, T. Tezuka, Power generation optimization in ASEAN by 2030, Energy Power Eng. 4 (4) (Jun. 2012) 226–232, https://doi.org/10.4236/EPE.2012.44031.

[16] Q. Zhang, K.N. Ishihara, B.C. Mclellan, T. Tezuka, Scenario analysis on future electricity supply and demand in Japan, Energy 38 (1) (2012) 376–385, https://doi.org/10.1016/j.energy.2011.11.046.

[17] Z.A. Muis, H. Hashim, Z.A. Manan, F.M. Taha, P.L. Douglas, Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target, Renew. Energy 35 (11) (Nov. 2010) 2562–2570, https://doi.org/10.1016/j.renene.2010.03.032.

[18] Q. Zhang, K.N. Ishihara, B.C. Mclellan, T. Tezuka, Scenario analysis on future electricity supply and demand in Japan, Energy 38 (1) (2012) 376–385, https://doi.org/10.1016/j.energy.2011.11.046.

[19] Q. Zhang, B.C. Mclellan, T. Tezuka, K.N. Ishihara, An integrated model for long-term power generation planning toward future smart electricity systems, Appl. Energy 112 (2013) 1424–1437, https://doi.org/10.1016/j.apenergy.2013.03.073.

[20] T. Luz, P. Moura, A. de Almeida, Multi-objective power generation expansion planning with high penetration of renewables, Renew. Sustain. Energy Rev. 81 (2018) 2637–2643, https://doi.org/10.1016/j.rser.2017.06.069.

[21] A. Poullikkas, G. Kourtis, I. Hadjipaschalis, A hybrid model for the optimum integration of renewable technologies in power generation systems, Energy Pol. 39 (2) (Feb. 2011) 926–935, https://doi.org/10.1016/j.enpol.2010.11.018.

[22] C. Barteczko-Hibbert, I. Bonis, M. Binns, C. Theodoropoulos, A. Azapagic, A multi-period mixed-integer linear optimisation of future electricity supply considering life cycle costs and environmental impacts, Appl. Energy 133 (Nov. 2014) 317–334, https://doi.org/10.1016/j.apenergy.2014.07.066.

[23] W.W. Purwanto, Y.W. Pratama, Y.S. Nugroho, G.F. Hertono, D. Hartono, T. Tezuka, Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources, Renew. Energy 81 (2015) 308e18.

[24] F. Amorim, A. Pina, a H. Gerbelov, P.P. da Silva, J. Vasconcelos, V. Martins, Electricity decarbonisation pathways for 2050 in Portugal: a TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling, Energy 69 (2014) 104e12.

[25] E.G. Dountio, P. Meukam, D.L.P. Tchaptchet, L.E.O. Ango, A. Simo, Electricity generation technology options under the greenhouse gases mitigation scenario: case study of Cameroon, Energy Strat. Rev. 13 (2016) 191e211.

[26] A. Hainoun, M.S. Aldin, S. Almoustafa, Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model, Energy Pol. 38 (4) (2010) 1701e14.

[27] M. Jaskolski, Modelling long-term technological transition of Polish power system using MARKAL: emission trade impact, Energy Pol. 97 (2016) 365e77.

[28] I. Komusanac, B. Cosic, N. Duic, Impact of high penetration of wind and solar PV generation on the country power system load: the case study of Croatia, Appl. Energy 184 (2016) 1470e82.

[29] M. McPherson, B. Karney, Long-term scenario alternatives and their implications: LEAP model application of Panama′ s electricity sector, Energy Pol. 68 (2014) 146e57.

[30] E. Merkel, D. Fehrenbach, R. McKenna, W. Fichtner, Modelling decentralised heat supply: an application and methodological extension in TIMES, Energy 73 (2014) 592e605.

[31] N.B. Park, S. Yun, C.J. Eui, An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector, Energy Pol. 52 (2013) 288e96.

[32] J. Tomaschek, R. Kober, U. Fahl, Y. Lozynskyy, Energy system modelling and GIS to build an integrated climate protection concept for Gauteng Province, South Africa, Energy Pol. 88 (2016) 445e55.

[33] M. Welsch, P. Deane, M. Howells, B.O. Gallachoir, F. Rogan, M. Bazilian, et al., Incorporating flexibility requirements into long-term energy system modelseA case study on high levels of renewable electricity penetration in Ireland, Appl. Energy 135 (2014) 600e15.

[34] G. Heinricha, L. Bassonc, B. Cohena, M. Howellsd, J. Petrie, Ranking and selection of power expansion alternatives for multiple objectives under uncertainty, Energy 32 (2007) 2350e69.

[35] H.B. Ren, W.S. Zhou, K. Nakagami, W.J. Gao, Q. Wu, Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects, Appl. Energy 87 (2010) 3642e51.

[36] C.H. Antunes, G.A. Martins, I.S. Brito, A multiple objective mixed integer linear programming model for power generation expansion planning, Energy 29 (2004) 613e27.

[37] V. Aryanpur, E. Shafiei, Optimal deployment of renewable electricity technologies in Iran and implications for emissions reductions, Energy 91 (2015) 882e93.

[38] A. Dhakouani, F. Gardumi, E. Znouda, C. Bouden, M. Howells, Long-term optimisation model of the Tunisian power system, Energy 141 (2017) 550e62.

[39] H.B. Ren, W.S. Zhou, K. Nakagami, W.J. Gao, Q. Wu, Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects, Appl. Energy 87 (2010) 3642e51. Ren et al.

[40] Q. Zhang, B.C. Mclellan, T. Tezuka, K.N. Ishihara, Economic and environmental analysis of power generation expansion in Japan considering Fukushima nuclear accident using a multi-objective optimization model, Energy 44 (1) (2012) 986e95.

[41] L. Ko, C.Y. Chen, V.C. Seow, Electrical power planning and scheduling in Taiwan based on the simulation results of multi-objective planning model, Int. J. Electr. Power Energy Syst. 55 (1) (2014) 331e40.

[42] W.W. Purwanto, Y.W. Pratama, Y.S. Nugroho, G.F. Hertono, D. Hartono, T. Tezuka, Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources, Renew. Energy 81 (2015) 308e18.

[43] M.S. Mahbub, D. Viesi, L. Crema, Designing optimized energy scenarios for an Italian Alpine valley: the case of Giudicarie Esteriori, Energy 116 (1) (2016) 236e49.

[44] Y.W. Pratama, W.W. Purwanto, T. Tezuka, B.C. McLellan, D. Hartono, A. Hidayatno, Y. Daud, Multi-objective optimization of a multiregional electricity system in an archipelagic state: the role of renewable energy in energy system sustainability, Renew. Sustain. Energy Rev. 77 (1) (2017) 423e39.

[45] H. Tekiner, D.W. Coit, F.A. Felder, Multi-period multi-objective electricity generation expansion planning problem with Monte-Carlo simulation, Elec. Power Syst. Res. 80 (12) (2010) 1394e405.

[46] H.A. Ibrahim, M.K. Ayomoh, Identification and prioritisation of electricity driving factors for power supply sustainability: a case of developing and underdeveloped nations, in: 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering, CSDE, 2021, pp. 1–6, https://doi.org/10.1109/CSDE53843.2021.9718450.

[47] A. Adeniyi, J. Ighalo, C. Adeyanju, Materials-to-product potentials for sustainable development in Nigeria, Int. J. Sustain. Eng. 14 (4) (2021) 664–671, https://doi.org/10.1080/19397038.2021.1896591.

[48] Statista, Nigeria: Annual Electricity Generation 2020-2021, Statista. Statista, 2022. https://www.statista.com/statistics/1294835/annual-electrical-energy-generation-in-nigeria/. (Accessed 28 July 2022).

[49] M. Umunna Nwachukwu, N. Flora Ezedinma, U. Jiburum, Comparative analysis of electricity consumption among residential, commercial and industrial sectors of the Nigeria's economy, J. Energy Technol. Pol. 4 (3) (2014) 7–13. https://www.iiste.org/Journals/index.php/JETP/article/view/11660/12005. (Accessed 28 July 2022).

[50] M.F. Akorede, O. Ibrahim, S.A. Amuda, A.O. Otuoze, B.J. Olufeagba, Current status and outlook of renewable energy development in Nigeria, Niger. J. Technol. 36 (2017) 196–212, https://doi.org/10.4314/njt.v36i1.25.

[51] T.C. Chineke, U.K. Okoro, Application of Sayigh “‘Universal Formula”’ for global solar radiation estimation in the Niger Delta region of Nigeria, Renew. Energy 35 (2010) 734–739.

[52] M. Shaaban, J. Petinrin, Renewable energy potentials in Nigeria: meeting rural energy needs, Renew. Sustain. Energy Rev. 29 (2014) 72–84.

[53] M.O. Dioha, I.J. Dioha, O.A. Olugboji, An assessment of Nigeria wind energy potential based on technical and financial analyses, J. Sustain. Energy 7 (2016) 53–57.

[54] M. Shaaban, J. Petinrin, Renewable energy potentials in Nigeria: meeting rural energy needs, Renew. Sustain. Energy Rev. 29 (2014) 72–84.

[55] R. Kela, K.M. Usman, A. Tijjani, Potentials of small hydro power in Nigeria: the current status and investment opportunities, Int. J. Sci. Eng. Res. 3 (2012) 1–5.

[56] J.U. Abaka, T.B. Ibraheem, H. Salmanu, O. Olokede, Hydropower potential of Nigeria, Int. J. Mod. Eng. Res. 7 (2017) 52–58.

[57] H. Ritchie, M. Roser, P. Rosado, CO_2 and Greenhouse Gas Emissions. Our World in Data, 2022. https://ourworldindata.org/co2-emissions. (Accessed 28 July 2022).

[58] D. Dokua Sasu, Carbon Emissions from Electricity Generation in Nigeria 2000-2020, Statista, 2022. https://www.statista.com/statistics/1307126/power-sector-carbon-emissions-in-nigeria/#:~:text=As%20of%202020%2C%20carbon%20emissions%20from%20the%20power,equivalent.%20This%20kept%20stable%20from%20the%20previous%20year. (Accessed 28 July 2022).

[59] R. Olurounbi, Bloomberg - Are You a Robot? Bloomberg.com, 2022. https://www.bloomberg.com/news/articles/2021-11-02/nigeria-targets-to-reach-net-zero-emissions-by-2060-buhari-says. (Accessed 28 July 2022).

[60] R. Olurounbi, Nigeria Unemployment Rate Rises to 33%, Second Highest on Global List, Bloomberg.com, 2022. https://www.bloomberg.com/news/articles/2021-03-15/nigeria-unemployment-rate-rises-to-second-highest-on-global-list. (Accessed 28 July 2022).

[61] O. Bamisile, Q. Huang, X. Xu, et al., An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030, Energy 197 (2020), 117172, https://doi.org/10.1016/j.energy.2020.117172.

[62] B. Salman, S. Nomanbhay, D. Foo, Carbon emissions pinch analysis (CEPA) for energy sector planning in Nigeria, Clean Technol. Environ. Policy 21 (1) (2018) 93–108, https://doi.org/10.1007/s10098-018-1620-5.

[63] P. Blechinger, C. Cader, P. Bertheau, Least-cost electrification modeling and planning—a case study for five Nigerian federal states, Proc. IEEE 107 (9) (2019) 1923–1940, https://doi.org/10.1109/jproc.2019.2924644.

[64] H. Ibrahim, G. Ye, Electricity demand and supply scenario analysis for Nigeria using long range energy alternatives planning (LEAP), J Sci Res Rep 19 (2) (2018) 1–12, https://doi.org/10.9734/jsrr/2018/39719.

[65] A.S. Sambo, Matching Electricity Supply with Demand in Nigeria, vol. 32, Fourth Quarter, 2008.

[66] A.O. Nathan Pelesai, A. Thank God, The dynamics of demand and supply of electricity in Nigeria, Int.Inst. Sci. Technol. Educat. (IISTE) 3 (2225–0565) (2013) 25–36. Available from: https://www.iiste.org/Journals/index.php/DCS/article/view/4663/4742. (Accessed 11 April 2022).

[67] C. Amlabu, J. Agber, C. Onah, S. Mohammed, Electric load forecasting: a case study of the Nigerian power sector, Int. J. Eng. Innovat. Technol. (IJEIT) 2 (13) (2013) [Accessed 31 March 2022].

[68] E.O. S, I.O. E, Analysis of Nigeria's national electricity demand forecast (2013-2030), Int. J. Sci. Technol. Res. 3 (2014) [Online]. Available: www.ijstr.org.

[69] B. Oyediran Oyelami, A. adedoyin Adewumi, Models for forecasting the demand and supply of electricity in Nigeria, Am. J. Model. Optimiz. 2 (1) (2014) 25–33, https://doi.org/10.12691/ajmo-2-1-4. http://pubs.sciepub.com/ajmo/2/1/4.

[70] N.V. Emodi, C.C. Emodi, G.P. Murthy, A.S.A. Emodi, Energy policy for low carbon development in Nigeria: a LEAP model application, Renew. Sustain. Energy Rev. 68 (Feb. 01, 2017) 247–261, https://doi.org/10.1016/j.rser.2016.09.118. Elsevier Ltd.

[71] A. Adedokun, in: Nigeria electricity forecast and vision 20: 2020: Evidence from ARIMA model 11, 2016, pp. 1027–1034, https://doi.org/10.1080/15567249.2014.912697, https://doi.org/10.1080/15567249.2014.912697 11.

[72] T. Moss, G. Portelance, Do African Countries Consume Less (Or More) Electricity than Their Income Levels Suggest? Center for Global Development | Ideas to Action, 2017. Available from: https://www.cgdev.org/blog/do-african-countries-consume-less-or-more-electricity-than-their-income-levels-suggest. (Accessed 10 April 2022).

[73] World Bank, Electric power consumption (kWh per capita) | Worlddataview.com. Worlddataview.com, Available: https://worlddataview.com/topics/environment/electric_power_consumption_kwh_per_capita, 2022. (Accessed 14 March 2022).

[74] M.O. Oseni, An analysis of the power sector performance in Nigeria, Renew. Sustain. Energy Rev. 15 (9) (2011) 4765–4774, https://doi.org/10.1016/j.rser.2011.07.075. Elsevier Ltd.

[75] Y.S. Mohammed, M.W. Mustafa, N. Bashir, A.S. Mokhtar, Renewable energy resources for distributed power generation in Nigeria: A review of the potential, Renew. Sustain. Energy Rev. 22 (2013) 257–268, https://doi.org/10.1016/j.rser.2013.01.020. Elsevier Ltd.

[76] N.O. Patrick, Unlocking the Potential of the Power Sector for Industrialization and Poverty Alleviation in Nigeria, UNCTAD. Unctad.org, 2017. https://unctad.org/webflyer/unlocking-potential-power-sector-industrialization-and-poverty-alleviation-nigeria. (Accessed 23 April 2022).

[77] M. Yetano Roche, in: Comparison of costs of electricity generation in Nigeria. Ng.boell.org, 2017. Available from: https://ng.boell.org/sites/default/files/true_cost_of_power_technical_report_final.pdf. (Accessed 17 April 2022). Publish.

[78] S.O. Oyedepo, Towards achieving energy for sustainable development in Nigeria, Renew. Sustain. Energy Rev. 34 (2014) 255–272, https://doi.org/10.1016/j.rser.2014.03.019. Elsevier Ltd.

[79] D. Ogunbiyi, M. Abiodun, *Nigeria Power Baseline Report*. Abuja: Advisory Power Team, 2015, pp. 1–30. Available from: https://mypower.ng/wp-content/uploads/2018/01/Baseline-Report.pdf. (Accessed 15 April 2022).

[80] A. Adebisi, F. Yusuf Yabo, Nigeria SE4ALL Action Agenda Final, Seforall.org, 2016. Available from: https://www.seforall.org/sites/default/files/NIGERIA_SE4ALL_ACTION_AGENDA_FINAL.pdf. (Accessed 14 May 2022).

[81] C. Raffaello, D. Irina, K. Rogers, J. Allen, Assessing Low-Carbon Development in Nigeria, Assessing Low-Carbon Development in Nigeria, Jun. 2013, https://doi.org/10.1596/978-0-8213-9973-6. http://documents.worldbank.org/curated/en/333931468332952975/Assessing-low-carbon-development-in-Nigeria-an-analysis-of-four-sectors.

[82] O. Patrick, O. Tolulolope, O. Sunny, O. Patrick, O. Tolulolope, O. Sunny, Smart grid technology and its possible applications to the Nigeria 330 kV power system, Smart Grid Renew. Energy 4 (2013) 391–397, https://doi.org/10.4236/SGRE.2013.45045.

[83] NASA, Surface Meteorology and Solar Energy, Atmospheric Science Data Center | Projects | SSE. Asdc.larc.nasa.gov, 2018. Available from: https://asdc.larc.nasa.gov/project/SSE. (Accessed 23 February 2022).

[84] D. Stetter, Enhancement of the REMix energy system model: global renewable energy potentials, optimized power plant siting and scenario validation, Published Dissertation, https://elib.dlr.de/92150/, 2014. (Accessed 29 March 2022).

[85] D. Bogdanov, C. Breyer, North-east Asian Super Grid for 100% Renewable Energy Supply: Optimal Mix of Energy Technologies for Electricity, Gas and Heat Supply Options, vol. 112, Energy Conversion and Management, Mar. 2016, pp. 176–190, https://doi.org/10.1016/j.enconman.2016.01.019.

[86] S. Afanasyeva, D. Bogdanov, C. Breyer, Relevance of PV with single-axis tracking for energy scenarios, Sol. Energy 173 (Oct. 2018) 173–191, https://doi.org/10.1016/j.solener.2018.07.029.

[87] U.B. Akuru, I.E. Onukwube, O.I. Okoro, E.S. Obe, Towards 100% renewable energy in Nigeria, Renew. Sustain. Energy Rev. 71 (2017) 943–953, https://doi.org/10.1016/j.rser.2016.12.123. Elsevier Ltd.

[88] A. Ajayi, S. Sowande, N. Oyewolu, C. Anyanechi, A Guide to the Nigerian Power Sector, KPMG, 2016. https://home.kpmg/ng/en/home/insights/2016/09/a-guide-to-the-nigerian-power-sector.html. (Accessed 21 April 2022).

[89] U.B. Akuru, A.O.E. Animalu, A.O.E. Animalu, Nigeria-Electricity-Supply, KPMG, 2021. Available from: https://home.kpmg/.../insights/2021/11/nigeria-electricity-supply-industry-highlights.html/. (Accessed 1 April 2022).

[90] NNPC, in: Crude oil reserves/production. Napims.nnpcgroup.com, 2022. Available from: https://napims.nnpcgroup.com/Pages/Crude-Oil-Reserves-Production.aspx. (Accessed 16 March 2022).

[91] A. Arnette, C. Zobel, An optimization model for regional renewable energy development, Renew. Sustain. Energy Rev. 16 (7) (2012) 4606–4615, https://doi.org/10.1016/j.rser.2012.04.014.

[92] ECN, Energy Implications of Vision 20: 2020 and beyond, Abuja, Abuja, 2014.

[93] M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick, E. O. Oladipo, Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways, Clim. Pol. 20 (7) (Aug. 2020) 846–865, https://doi.org/10.1080/14693062.2019.1661818/SUPPL_FILE/TCPO_A_1661818_SM9019.DOCX.

[94] S. Oke, M. Ayomoh, O. Akanbi, F. Oyawale, Application of hybrid structural interaction matrix to quality management, Int. J. Prod. Qual. Manag. 3 (3) (2008) 275, https://doi.org/10.1504/ijpqm.2008.017499.

[95] N.B. Park, S.J. Yun, E.C. Jeon, An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector, Energy Pol. 52 (Jan. 2013) 288–296, https://doi.org/10.1016/J.ENPOL.2012.09.021.

[96] TAVANIR Holding Company, Electricity Power Industry in Iran (2015-2016), TAVANIR, Tehran, 2016. Available from: http://amar.tavanir.org.ir/pages/report/stat94/sanatebargh/sanatebargh%20l/sanatl.pdf. (Accessed 1 April 2022).

[97] Renewable Energy Organization of Iran (SUNA) – Kish Solar Trading Company, Available from: http://kishsolar.com/renewable-energy-organization-of-iran-suna/?lang=en, 2012. (Accessed 1 April 2022).

[98] IEA and NEA, Projected Cost of Generating Electricity, IEA, Paris, 2015. Available from: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf. (Accessed 1 April 2022).

[99] IEA-ETSAP, Technology Brief: Coal-Fired Power, IEA-ETSAP, 2010. Available from: http://www.etsap.org/E-techDS/PDF/E01-coal-fired-power-GS-AD-gct.pdf. (Accessed 1 April 2022).

[100] IEA, Renewable Energy Essentials: Geothermal, IEA, Paris, 2010. Available from: https://www.iea.org/publications/freepublications/publication/Geothermal_Essentials.pdf. (Accessed 1 April 2022).

[101] IEA. Technology, Roadmap: Solar Thermal Electricity, IEA, Paris, 2014. Available from: https://www.iea.org/media/freepublications/technologyroadmaps/TechnologyRoadmapSolarThermalElectricity_2014edition4.pdf. (Accessed 1 April 2022).

[102] IEA, Renewable Energy Essentials: Hydropower, IEA, Paris, 2010. Available from: http://www.iea.org/publications/freepublications/publication/hydropower_essentials.pdf. (Accessed 1 April 2022).

[103] M.Y. Roche, N. Ude, D.I. Ofoegbu, True Cost of Electricity in Nigeria: Comparison of Costs of Electricity Generation in Nigeria, Nigerian Economic Summit Group and Heinrich Böll Stiftung Nigeria, Abuja, 2017.

[104] Y.M. Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick, E. O. Oladipo, Achieving sustainable development goals in Nigeria's power sector: assessment of transition pathways, Clim. Pol. (2019) 1–20, https://doi.org/10.1080/14693062.2019.1661818.

[105] IEA, Energy Technology Perspectives Catalysing Energy Technology Transformations: OECD/IEA, 2017. Available from: https://www.iea.org/media/freepublications/technologyroadmaps/EnergyTechnologyPerspectives2017-Analysis-IEA2017edition4.pdf. (Accessed 1 April 2022).

[106] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, C. Breyer, A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030, J. Clean. Prod. 199 (2018) 687–704, https://doi.org/10.1016/j.jclepro.2018.07.159.

[107] S.J.W. Klein, S. Whalley, Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis, Energy Pol. 79 (Apr. 2015) 127–149, https://doi.org/10.1016/J.ENPOL.2015.01.007.
[108] IPCC, Guidelines for National Greenhouse Gas Inventories, 2006. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. (Accessed 1 April 2022).
[109] EIA, Annual Energy Outlook 2022 - U.S. Energy Information Administration (EIA), 2022. Available from: https://www.eia.gov/outlooks/aeo/. (Accessed 1 April 2022).
[110] S. Oke, M. Ayomoh, The hybrid structural interaction matrix, Int. J. Qual. Reliab. Manag. 22 (6) (2005) 607–625, https://doi.org/10.1108/02656710510604917.
[111] I. Tambari, M. Dioha, P. Failler, Renewable energy scenarios for sustainable electricity supply in Nigeria, Energy Clim. Change 1 (2020), 100017, https://doi.org/10.1016/j.egycc.2020.100017.