

Article

Modeling Long-Term Electricity Generation Planning to Reduce Carbon Dioxide Emissions in Nigeria

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Abstract: The most recent assessments conducted by the International Energy Agency indicate that natural gas accounts for the majority of Nigeria's fossil fuel-derived electricity generation, with crude oil serving mostly as a backup source. Fossil fuel-generated electricity represents 80% of the country's total. In addition, carbon dioxide (CO₂) emissions in Nigeria in 2018 (101.3014 Mtons) demonstrated a 3.83% increase from 2017. The purpose of this study is to suggest an alternate energy supply mix to meet future electrical demand and reduce CO₂ emissions in Nigeria. The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) was used in this study to model two case situations of the energy supply systems in Nigeria to determine the best energy supply technology to meet future demand. The Simplified Approach to Estimating Electricity Generation's External Costs and Impacts (SIMPACTS) code is also used to estimate the environmental impacts and resulting damage costs during normal operation of various electricity generation technologies. Results of the first scenario show that gas and oil power plants are the optimal choice for Nigeria to meet future energy needs with no bound on CO₂ emission. If Nigeria adopts CO₂ emission restrictions to comply with the Paris Agreement's target of decreasing worldwide mean temperature rise to 1.5 °C, the best option is nuclear power plants (NPPs). The MESSAGE results demonstrate that both fossil fuels and NPPs are the optimal electricity-generating technologies to meet Nigeria's future energy demand. The SIMPACTS code results demonstrate that NPPs have the lowest damage costs because of their low environmental impact during normal operation. Therefore, NPP technology is the most environmentally friendly technology and the best choice for the optimization of future electrical technology to meet the demand. The result from this study will serve as a reference source in modeling long-term energy mix therefore reducing CO₂ emission in Nigeria.

Keywords: energy modeling; MESSAGE; SIMPACTS; CO₂ emission; Nigeria energy; environmental impact



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1. Introduction

Known as the “Giant of Africa”, Nigeria is located on Africa's west coast, with total size of 923,766 km² comprising of 910,768 km² land mass and 13,000 km² water bodies [1]. As of 2021, the current population is 211,400,708 (a 2.55% increase from 2020). The total GDP of Nigeria in 2019 was \$448.12 billion, demonstrating a 12.8% rise from 2018 [2]. In 2019, the gross domestic product (GDP) growth rate was 2.21%, a 2.09% increase from 2018. In 2019, the GDP per capita was \$2230, a 9.97% increase from 2018 [3]. The Statistical Review of World Energy 2019 by British Petroleum (BP) shows that Nigeria is Africa's top oil producer [4]. It boasts Africa's greatest natural gas reserves. It was rated as fifth-largest liquefied natural gas exporter in the world in 2018. The country's economy majorly relies on crude oil and natural gas reserves [5]. However, despite being Africa's largest crude

oil producer, Nigeria's output is hampered by intermittent supply disruptions. Nigeria's economy is primarily reliant on oil revenue, therefore variations in crude oil prices have a significant impact. The country's crude oil and natural gas exports are expected to generate \$55 billion in 2018, according to the International Monetary Fund (\$23 billion higher than that in 2016) [5]. In 2017, Nigeria's electrical generation capability was 12,664 MW, with fossil fuels accounting for 10,522 MW (83 percent), hydroelectricity 2110 MW (16 percent), and solar, wind, biomass, and waste sources accounting for 32 MW (1 percent). Natural gas provides the majority of Nigeria's fossil fuel-based energy generation. The most recent emission projections, based on the revised business-as-usual (BAU) scenario and low carbon scenario presented in Nigeria's Third National Communication, show that they will continue to increase until 2030 and that reductions will not be enough to meet the upper range of the national mitigation targets. Nigeria needs to increase the scale of its climate action to align with the Paris Agreement temperature target of regulating the worldwide mean temperature rise of 1.5 °C [6]. To cope with economic development and to reduce GHG emissions, the need for renewable and nuclear energy in Nigeria's energy mix is clear. Therefore, between 2005 and 2028, the Nigerian government intends to generate 4800 MW from nuclear power. To realize its set goal, the government engaged a contract with the Government of Russian State Atomic Energy Corporation (ROSATOM) to build and operate twin nuclear power plants (NPPs) and a flexible research reactor compound for its nuclear research reactor. Four power reactor units will be constructed by ROSATOM with a total capability of 4800 MW. The VVER-1200 reactor is to be supplied by Atomstroyexport. Two candidate sites have been selected for the planned NPPs namely the Geregu site in Kogi State and the Itu site in Akwa Ibom State. Each facility will accommodate nuclear reactors with a combined capacity of 2400 megawatts (MW). [7]. In Nigeria, government support and investor interest in solar power projects has grown in recent years as a method to alleviate natural gas supply constraints and improve access to electricity in remote and rural communities. A \$75 million award is being jointly sponsored by the Nigerian government, the Rural Electrification Agency, and the Nigeria Electrification Project (supported by the World Bank) to stimulate off-grid solar projects therefore minimizing the dependence on kerosene and diesel consumption for lighting and backup power [8].

A study was conducted to match electricity supply with electrical demand in Nigeria [5]. MESSAGE code was employed to simulate Nigeria's long-term energy plan and the viability of its nuclear power resources. The results demonstrated that the ratio of hydroelectricity to the total generated capability decreased from 31.30% to 11% in 2005 and 2030. In addition, the ratio of fossil fuel electricity capability increased from 68.30% to 82.15% in 2005 and 2010, then decreased in 2030 to 62.95%. According to the study, coal and nuclear power (neither of which are currently used for power generation) are expected to contribute 15.6% and 6.7% of electricity production by 2030. Solar energy and wind power are also expected to contribute 8.3% and 1.8% by 2030 [9]. Another study by Baraka et al. [10] used the MESSAGE code to model energy supply alternatives for electricity production in Tanzania from 2010 to 2040 [10]. Three economic scenarios developed for modeling purposes: Business as usual (BAU), low economic consumption (LEC), and high economic growth (HEC). Dry weather scenarios were also established to explore how the national electrical system operates under dry weather situations. The outcomes of the model suggested that as the expected final power demand for the three scenarios increases, its overall installed capability also increases from the base 804.2 MW by 9.05%, 8.46%, and 9.8%, respectively. Therefore, the model results show the dominance of hydroelectricity, coal, fossil, and geo-thermal energy has the minimum energy supply alternatives in terms of cost of electricity production in all situations [10]. A study of Mongolia's long-term energy plan with NPPs using the MESSAGE code aimed to create the first model of Mongolia's energy modeling to predict the feasibility of introducing nuclear power in its energy circle and to fulfill total electricity demand by 2040. The study also aimed to predict what emerging technologies could meet future electricity demand. After weighing the costs and CO₂ emissions of various generation technologies, nuclear power technology was selected

as the best option to meet the electricity shortage. Nuclear power had a cost advantage in terms of the effect of fuel prices on power generation costs. However, coal continues to be a favored resource over NPPs because of its low price and abundant deposits in Mongolia [11]. Liun et al. [12], used the SIMPACTS code in his study to evaluate the environmental effects of major electricity generation technologies in Java, Indonesia [13]. That study's main purpose was to explore the future optimal energy mix in Indonesia using an approach that combined both economic and environmental aspects in long-term energy system analyses. The study concluded that the Muria NPP had the lowest cost of damage among all electricity generation alternatives investigated. Another study used the SIMPACTS software to estimate the effects in terms of costs from various electricity generation technologies [14]. That research assessed the externalities from several power plants in metropolitan area of Mexico City by developing a unique system to apply the impact pathway analysis (IPA) of SIMPACTS to evaluate the resulting cost resulting in damage from various plants. The estimate showed that the annual total cost was \$71 million. A similar study was conducted (using IPA) to determine the damage costs of Syrian electricity generation [15]. The results demonstrated that the environmental impacts could add considerable external costs to the typical generation cost, of which externalities vary between US 2.5 and 0.07 cents/kWh. There is an argument around the use of nuclear power plants in the energy mix. After Chernobyl accident in 1986, some countries were turned off their nuclear reactors; the number of reactor connected to grid was sharply decreased [16]. On the other hand, some countries see nuclear energy as a worthy alternative to fulfill their sustainability and reliability of energy, as well as reducing air pollutants, greenhouse gases [17]. A Recent study on public perception to nuclear power plants in Nigeria shows 44% of the respondents did not support the country's decision to introduce nuclear power as part of its electricity generation mix [18].

This study's objective is to use the MESSAGE software to assess the BAU technology used to generate electricity in Nigeria without any constraints on the CO₂ emissions. In addition, the external cost of environmental impacts will be calculated using the SIMPACTS software. Constraints on CO₂ emissions for oil and gas power plants will be applied and the best choice of technology that can generate electricity with minimal external cost and less environmental impacts will be determined. According to the Nigeria climate transparency report of 2020, worldwide CO₂ emissions must be reduce by 45% less than the 2010 ranks by 2030 to achieve the Paris agreement on net-zero by 2050 [6]. Thus, predicting Nigeria's long-term energy needs and estimating its associated environmental impact therefore reducing carbon emission is vital. Various research has been conducted using different energy modeling tools with the aim of modeling long-term electricity generation technologies to meet the future electricity demand of Nigeria; however, no studies conducted in assessing the environmental impacts and damage cost associated with such technologies therefore reducing carbon dioxide emission emanating from existing technology. In this study, we evaluate the best choice of technology that can be used to generate electricity based on two criteria, cost and environmental impact. Findings from this study will serve as a reference point for modeling long term energy mix and reduce CO₂ emission. This study consists of four sections. The Section 1 describes the energy situation in Nigeria and a literature review of our work. The Section 2 presents the methods and input data for both programs. The Section 3 discusses the results obtained from the two software. The Section 4 summarizes the conclusion of this study.

2. Materials and Methods

The methods employed in this paper were divided into two scenarios. The first scenario was the current technologies used in Nigeria to generate electricity. The second scenario involved applying CO₂ emission limits to the oil and gas power plants. In each scenario, two software techniques were used. The MESSAGE code was used to find the optimal energy mix of technologies to meet the future demand for electricity. The

SIMPACTS code was used to estimate the environmental impact and damage costs of these technologies.

2.1. First Scenario (No Carbon Dioxide Emission Constraints)

2.1.1. MESSAGE Input Data

The MESSAGE software is used to create optimization models for energy supply systems. These models can be developed at state, sub regional, and regional levels to evaluate various energy system development strategies in the short or long term while considering their overall environmental impact. MESSAGE is a system engineering optimization model that optimizes a linear objective function under certain constraints or linear equalities and inequalities based on decision variables. The objective function may be to minimize costs or maximize profits, and several optimization parameters are applied where the optimal solution would be sought [19]. The objective function is obtained from the system cost. For each period (denoted as “t”), the following information is recorded:

- Fixed and variable operation and maintenance costs
- Investment and penalty costs, and taxes induced by regulation

$$\text{Total system cost} = \sum_{t=1}^T \beta \times \sum_{i=1}^n C_{it} \times X_{it} \quad (1)$$

where $\sum_{i=1}^n C_{it} \times X_{it}$ is the sum of costs incurred in period (t) and $\beta = \frac{1}{1+r}$. In Equation (1) [20–22], (r) is the discount rate.

The performance of a linear programming solution may be an infeasible solution because of restrictions that prevent the program from finding the optimal solution. These restrictions are an unbounded solution (where the objective function takes arbitrary values) or an optimal solution (where the objective function value is optimized). The decision variables, on the other hand, cannot constantly vary and must take only discrete values. MESSAGE allows the use of mixed-integer programming (MIP) when certain variables in an optimization problem are integers. Unlike in linear programming, where large-scale problems are solved regularly, MIP is a methodology where finding the best solution is difficult. Large-scale MIPs can take a long time to solve an optimization problem, or it may never be solved. Figure 1 illustrates the different steps involved in converting various energy resources to different energy forms using several technologies to produce the required electricity in Nigeria using the available resources. The energy chain consists of various levels of resources: primary, secondary, and final energy forms. All resources are useful for industrial and commercial purposes. Various resources are transformed from one energy level to another using different technologies from production, import, and extraction at the resources level, following processing and supply at the primary level. Power production technologies are initiated from primary to secondary energy levels to produce electricity, gas, and oil. Transmission and distribution occurs at the final energy level, with the useful demand of electricity and various resources used for commercial and industrial purposes. Energy technology is a process of transforming one energy form into another energy form. Several skills are employed in producing and transforming various energy forms from the initial resources level to the final energy demand level. The various technologies employed in this study are represented in Figure 1. The input data were divided into general input data and technology input data for both scenarios. The general input data comprised the base year, the modeling period, the discount rate, the resources available, and the energy forms at various levels (primary, secondary, and final) as well as the final demand. The technology input data consisted of the various technologies used in converting resources to final electricity and demand. Table 1 summarizes the basic input data used in MESSAGE to predict future energy needs. In this study, the available resources for energy production in Nigeria were first modeled for electricity generation from oil and gas resources over various energy forms. The final demand for all the available resources used for energy and industrial consumption was predicted using the MESSAGE code.

Future energy demand is the most important input parameter in the optimization process for the future energy mix.

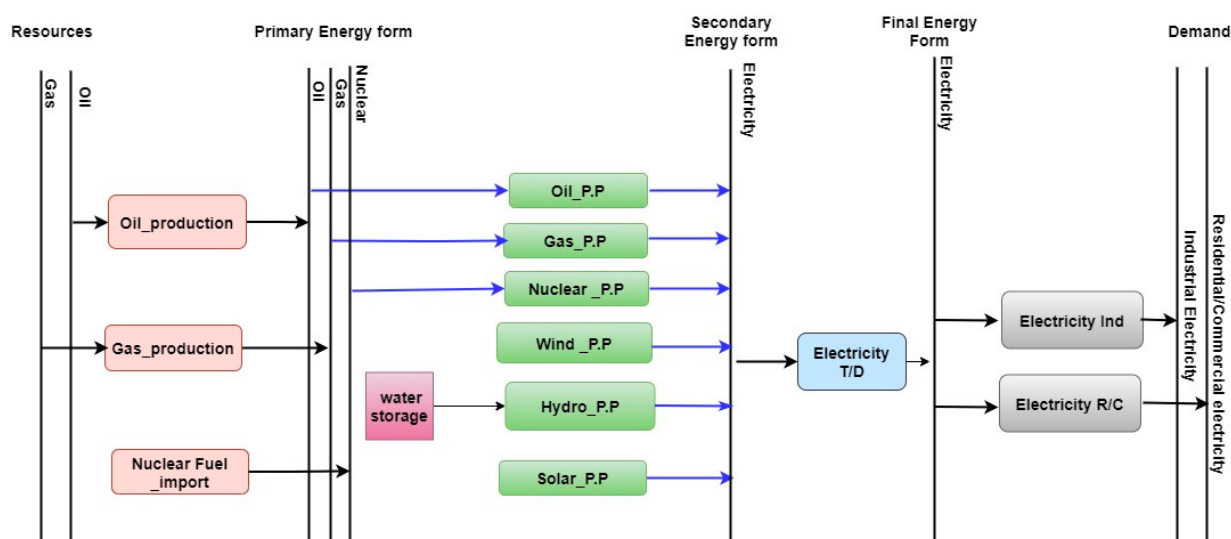


Figure 1. The energy chain modeling of Nigeria showing various energy resources and forms simulated in MESSAGE code for various power plants to final electricity.

Table 1. General input data used in MESSAGE code for both scenarios using a base year of 2015 and modeling period of 45 years.

Parameter	Input
Base Year	2015
Modeling Period	2015 to 2060
Discount Rate	15% [23]
Available Resources Used	Oil and Gas
Energy Forms	Resources, Primary, Secondary, and Final
Demand	Final Demand for Electricity

The first model year is referred to as the base year, and the modeling period represents the period of prediction commencing from the base year up to the last model year. In this study, the base year is 2015, the last model year is 2060, and the time step is 1 year. The discount rate represents the rate at which the value of the plant decreases over time due to depreciation in the value of the plant over time. As a result, discount rates are employed to assign a significance to impending cash flows. The lesser the value attached to future savings in today's judgments, the greater the discount rate. As a result, great discount rates create energy effectiveness initiatives and regulations appear less appealing. MESSAGE allows four types of data sets to give values to any data entity. These data types are; constant (c) which is a fixed number used during the modeling period in the case study; Time series (ts) which is used to enter the required values for each year in the case study; Constant growth (cg) which is the average annual growth rate, which indicates the increase in the value of demand over the modeling period; and periodic growth (pg) which defines a set of average annual growth rates for the specific number of periods in the study [24]. This study adopted the constant growth method to enter values for all future electricity demands which is in line with the population growth of Nigeria. Average annual growth rate (AAGR) of population in Nigeria is 2.6% which was calculated using the population data obtained from Energy Information Administration (EIA) from 1980 to 2015 while the Average constant growth rate in electricity demand is 5.5% which was also calculated in the same manner. The electricity demand data from 1980 until 2015 (base year) were collected and plotted in Figure 2 and used to calculate the average annual growth rate which is consistent with the population growth rate adopted for this study. The initial value of

future electricity demand in 2016 was 25,941.970 GWh [24], with a constant mean yearly increase of 5.5% throughout the modeling age. The technology input data are divided into two tabs. The first is the activity tab describing the input and output of the technology, the loss during the transformation process, the variable operations, the maintenance costs, and the output level in the base year. Table 2 describes the activity tab input parameters for every type of technology evaluated in this study. The second is the capacity tab that describes the first and last years in which the technology can be built, the plant capacity factor, the plant lifetime, the investment costs and fixed costs, the historical capacity, and the minimum power. Table 2 describes the capacity tab input parameters for each type of technology evaluated in this study.

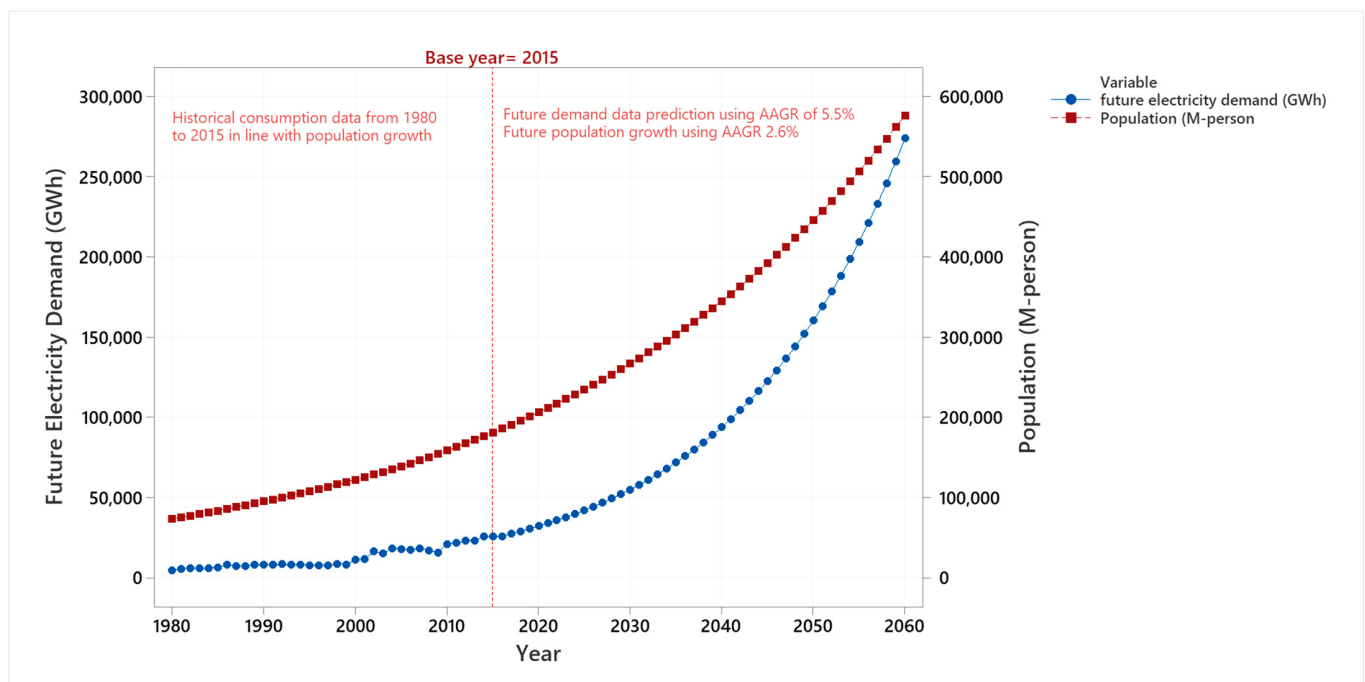


Figure 2. Prediction of future electricity demand for Nigeria from 2015 to 2060 using average annual growth rate calculated from historical data obtained from Energy Information Administration from 1980 to 2015 [24].

Table 2. Technology parameters including plant capacity factor, plant life, investment and variable cost simulated in MESSAGE code.

Technology Name	Plant Capacity Factor	Plant Life (Years)	Investment Cost (USD/kW) [25]	Variable Cost (USD/MWh) [25]	Loss	Output Level in the Base Year (GWh)
Electricity distribution (Elect-TD)	N/A	60	1000	10	20%	25,941.97
Oil power plant (Oil-PP)	0.3	35	1563	4.7	50%	3764.277
Gas power plant (Gas-PP)	0.3	40	1175	6.2	50%	21,330.903
Solar power plant (Solar-PP)	0.2	25	1313	0	0	24
Hydropower plant (Hydro)	0.3	70	5316	0	0	3
Wind power plant	0.15	20	1265	10	0	5663
Nuclear power plant (Nuc-PP)	0.9	60	4800	2.37	10%	N/A

2.1.2. SIMPACTS Input Data

SIMPACTS is a code developed by the IAEA to estimate and quantify the health and environmental implications of various energy generation methods, as well as the associated damage costs. This code is especially suitable for comparing fossil, nuclear, and hydroelectric power plants. It consists of different modules to estimate the effects of routine pollutants from energy facilities on human health, agricultural crops, and buildings. It can be used to compare the cost-effectiveness of fossil, nuclear, and renewable energy production, as well as the establishment of new power plants and environmental mitigation policies. It calculates both internal and external costs. The code requires a small amount of input data, simplifying its use and applications. The model uses the impact pathway analysis (IPA) method for airborne emissions from fossil or nuclear plants, in which the emission source is characterized, and a catalog of flying discharges is prepared. The variations in ambient absorptions of different contaminants are estimated using atmospheric dispersion and deposition models. As a result, exposure–response functions (ERFs) are used to link a shift in contaminant attentiveness to a physical effect on the receptors in question. SIMPACTS calculates the physical effects and associated cost resulting from damage to human health, agricultural crops, and receptors associated with routine air emissions (e.g., particulates, SO₂, NO_x, CO₂, etc.) from fossil fuels, typical operational releases of radioactivity to air or surface waters from NPPs, and external costs of hydropower projects in terms of impact from hypothetical dam failure accidents. The methodology is termed IPA, where physical impacts (health consequences) and external costs (damages) are calculated by tracing the fate of a pollutant from the point of emission to its environmental interaction, dispersion and chemical transformation, and receptor uptake in terms of exposure as well as estimating the resulting effects and resulting damage costs related with such emissions [26].

The damage cost is calculated by the product of total number of cases or impacts with the associated unit costs. Equation (2) represents the effect on human health while Equation (3) represents the impact on receptor r across the entire domain.

$$I_{ik} = G^2 \times \sum_{x=1}^n \sum_{y=1}^n \rho_{xy} \times erf_{ik \cdot C_{ixy}} \quad (2)$$

where G is the grid size for each exposure area A_{xy} within the impact region (km). The population density is ρ_{xy} within the exposure area (person/km). The unit health impact is erf_{ik} for type k and classes i (cases/year per person/ $\mu\text{g}/\text{m}^3$). The surge in ground-level ambient air concentration is C_{ixy} within the exposure area ($\mu\text{g}/\text{m}^3$) [27].

$$I_r = \sum_{x=1}^n \sum_{y=1}^n R_{rxy} \times erf_{rxy \cdot C_{xy}} \quad (3)$$

where R_{rxy} is the total annual crop production (tons per year) of receptor r within the exposure area A_{xy} , erf_{rxy} is the erf of receptor type r (% yield change per $\mu\text{g}/\text{m}^3$), and C_{xy} is the incremental concentration of the pollutants SO₂ within the exposure area ($\mu\text{g}/\text{m}^3$). Equation (4) represents the external cost (ECY) owing to the health impact and Equation (5) represents the external cost owing to the agricultural impact.

$$ECY_{ik} = I_{ik} \times U_k \quad (4)$$

where I_{ik} is the health effect for type k and classes i (cases/year), U_k is the unit cost for health effect k (dollar/case) [27].

$$ECY_r = \sum_{x=1}^n \sum_{y=1}^n I_{rxy} \times U_r \quad (5)$$

where I_{rxy} is the annual crop yield reduction (tons per year) of receptor type r within the exposure area A_{xy} , and U_r is unit cost of receptor type r (dollar per ton).

In this scenario, two types of power plants were simulated and the environmental impact of each was measured. The first power plant was the Egbin fossil power plant in

Lagos State; It is Nigeria's and the West African sub-region's largest electricity-generating station which supplies over 30 percent of the overall existing electricity generation to the country's national grid and comprises six units, each producing 220 MW with the overall designed capability of 1320 MW [28]. Table 3 shows the emission and dispersion input data required to simulate the fossil power plant in SIMPACTS in addition to the health and agricultural impacts. The second power plant is the Jebba hydroelectric power plant. It is located 100 km downstream of the Kainji Dam in Niger State. The plant design capacity is 578.4 MWe from six turbines (each turbine generates 96.4 MW). The power of this plant is enough to power 364,000 homes. This plant is one of Nigeria's most cost-effective electricity sources. It was commissioned in 1985 [29]. Table 4 is a summary of the input information used to simulate the Jebba hydropower plant.

Table 3. Input data of Egbin fossil power plant simulated in SIMPACT code.

Domain Data			
Domain Name	Egbin Fossil Power Station		
Time Frame	Full year		
Cell Size	50 × 50 km		
Latitude	6.5635°		
Longitude	−3.6151°		
Emission and Dispersion			
Base elevation	10 m		
Stack Height [30]	40 m		
Stack Diameter	8.3 m		
Exit Temperature [31]	541.15 °C		
Exit Velocity [31]	40.96 m/s		
SO ₂ emissions [32]	33.588 kg/h		
NOx emissions [32]	2928.6 kg/h		
PM10 emissions [32]	65.772 kg/h		
Month	Ozone (O ₃) Concentration	Ammonia (NH ₃) Concentration	
All year	80 ppb (default)	10 ppb (default)	
Health Impacts			
Lagos	Ogun		
Population Density = 3345/km ² [33]	Population Density = 311.3/km ² [33]		

Table 4. Input data for Jebba hydropower plant simulated in SIMPACT code.

Site Location and Cost Data			
Economic defaults from GDP per Capita [34]		NIGERIA \$2097 per capita	
Hydro Power Plant Data			
Plant Capacity [35]		578.4 MW	
Capacity Factor [36]		83%	
Lifetime		50 years	
Dam Data			
Reservoir inundated area [37]		350 km ²	
Average Dam failure rate (default)		0.0001 fraction	
Average accident warning time (default)		1.5 h	
Population Data			
Population displaced		28,875 persons	
Share of population resettled/compensated		60%	
Population at risk in the event of accident		47,200 persons	
Value of statistical life		\$128,839.11	
Land Use Data (type)			
Region type		Tropical	
Type of Terrain		Flatlands	
Agricultural Products [38]			
Maize Corn	2800 tons/year	8 \$/ton	
Beans	4200 tons/year	12 \$/ton	
Onions	3500 tons/year	10 \$/ton	
Rice	5600 tons/year	16 \$/ton	

2.2. Second Scenario (with Carbon Dioxide Emission Constraints)

In this scenario, the CO₂ emissions from oil and gas power plants were restricted with a certain value. Figure 3 shows the relationship between CO₂ emissions and the electricity generated by fossil power plants in Nigeria from 1980 to 2018.

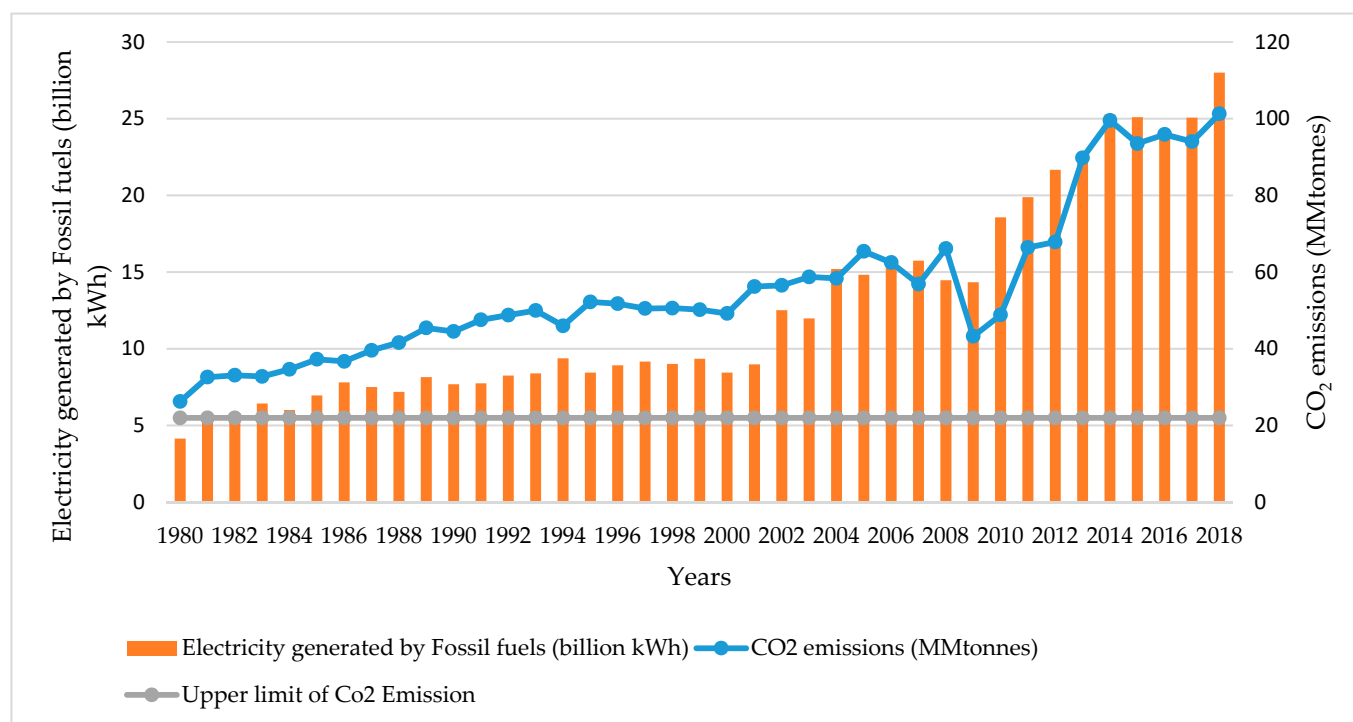


Figure 3. Showing the trend of increasing CO₂ emissions concurrent with the increasing electricity generated by fossil fuels in Nigeria from 1980 to 2018 [39].

2.2.1. MESSAGE Input Data

Constraints are limits or restrictions imposed on the decision variables. The restrictions in MESSAGE represent various limitations on technology (including emission limits imposed by environmental regulations). An important constraint in a model of an energy supply system is the satisfaction of demand. Depending on the model, the energy demand can be expressed at the level of final energy forms (demand for gas, demand for electricity, etc.) or at the useful energy level (demand for transportation by cars, demand for residential heat, demand for industrial heat, etc.). The constraint is that supply must be at least equal to demand at each period “ t ”.

$$\sum_{i=1}^{i=n} S_{ij} \times X_{it} \geq D_{jt} \quad (6)$$

where D_{jt} is the demand for energy form (j) in period (t), X_{it} is the activity of technology (i) in period (t), and S_{ij} is the rate at which technology (i) produces energy form (j) [20]. In this study, the upper limit of CO₂ emissions was determined from information in the Nigerian climate transparency report 2020 and the Paris Agreement [6]. To keep its determinations to restrict world average temperature rise to 1.5 °C on track, global CO₂ emissions must be 45 percent lower than 2010 levels by 2030 and net-zero by 2050. Therefore, it was assumed that the upper limit of CO₂ emissions shall not exceed 21,983.55 kton [6,40]. In all cases, the input data used in MESSAGE code includes the historical data of electricity production for various electricity generation sources from 1980 to 2015 obtained from energy information administration (EIA) alongside other defaults values and plant specific data calculated by the code. The historical data obtained were used for prediction of future electricity generated by each technology for both scenarios throughout the modeling period. As

shown in Figure 4, the gray line represents the upper limit assumed in the MESSAGE code for a fossil power plant. CO₂ emission intensities were below 400 g/kWh in the majority of natural gas combined cycle power plants [41], whereas oil power plants had emission intensities below 644 g/kWh [42].

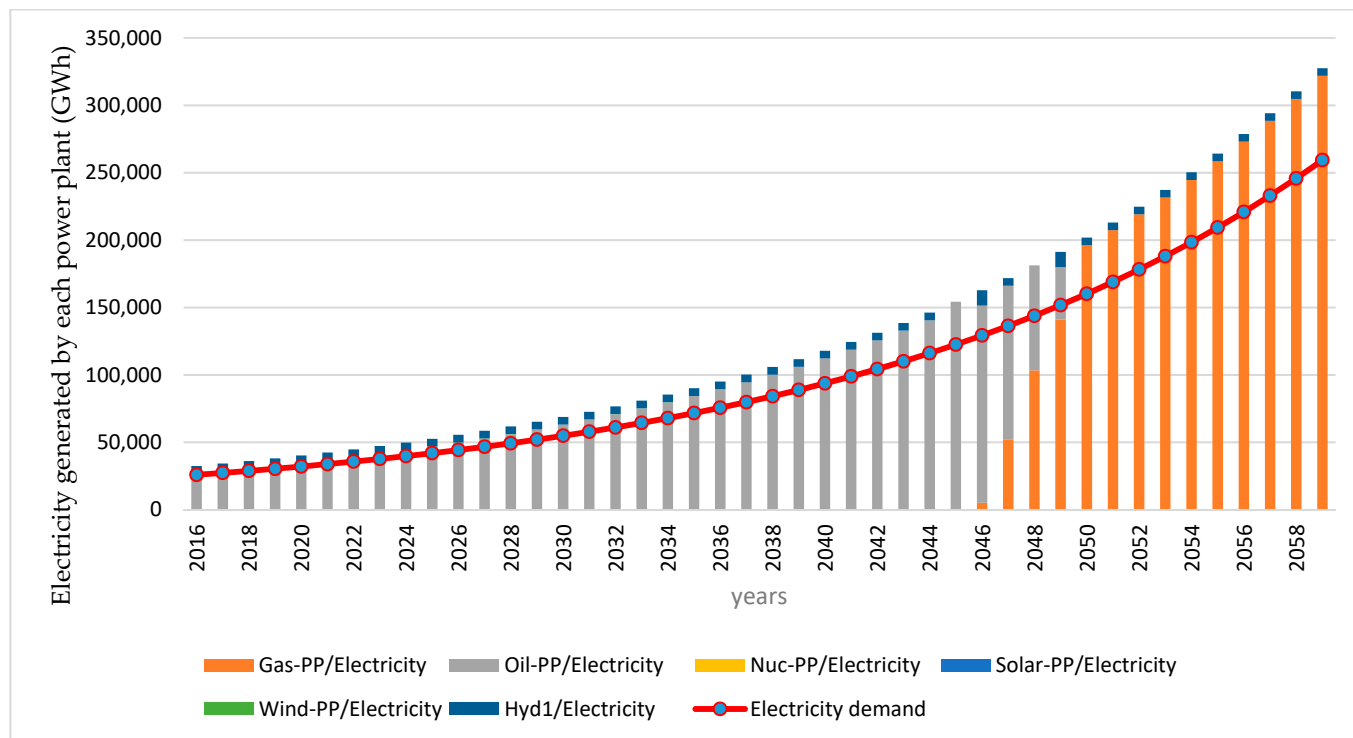


Figure 4. Increase in electricity production and demand from all power plants without a limit on CO₂ emission using MESSAGE code for the modeling period under study.

2.2.2. SIMPACT Input Data

In this scenario, an NPP was introduced as an alternative clean energy for oil and gas power plants. The external cost for environmental impacts was calculated by SIMPACTS. The SIMPACTS software can estimate the environmental impact of radioactive releases from NPPs deposited on the ground and on vegetation during routine operation. These radioactive discharges have an external and internal impact on human health, as radionuclides in the air and food are inhaled and eaten, respectively. Nigeria has plans to construct an NPP at the Geregú site. According to the agreement between Nigeria and ROSATOM, two units of VVER-1200 reactors will be constructed. In this study, a similar unit was simulated using SIMPACTS software. In all cases, the input data used in SIMPACTS code to estimate the environmental impact and damage cost associated with various electricity generation technologies from fossil, hydro and nuclear power plants includes plant specific data for particulate emission and dispersion from Egbin fossil power plant obtained from previous literature, population density around the cell size of the plant, the area of coverage estimated using google earth as well as other SIMPACTS default values which provides the resulting damage cost; for Jebba hydro power plant includes plant capacity factor, reservoir inundated area and some agricultural production obtained from previous research alongside other defaults data provided in the SIMPACTS code; for the proposed Geregú Nuclear power plant includes plants stack height, exit velocity emission rate of various radionuclides obtained from previous studies of the same proposed reactor type, population density of the area as well as export share of some agricultural production obtained from previous research alongside other defaults data with respect to health risk and damage cost estimated by the SIMPACTS code. Table 5 summarizes the input data using SIMPACTS to simulate the proposed Geregú NPP to assess the environmental impacts.

Table 5. Input data required to assess environmental impacts and associated health and damage costs of radionuclide emissions from a nuclear power plant using SIMPACT code.

Domain Data		
Domain Name	Nigeria Nuclear Modeling	
Time Frame	Full year	
Cell Size	50 × 50 km	
Latitude	49.3°	
Longitude	−1.9°	
Emission and Dispersion		
Base elevation	20 m	
Stack Height [43]	100 m	
Stack Diameter	3 m	
Exit Temperature	177 °C	
Exit Velocity [44]	15 m/s	
Emission cycle	Constant	
Emission rate unit [45]	GBq/year	
³ H emissions	3080 GBq/year	
¹⁴ C emissions	1050 GBq/year	
¹³¹ I emissions	0.342 GBq/year	
¹³³ I emissions	0.640 GBq/year	
⁶⁰ Co emissions	0.102 GBq/year	
⁸⁵ Kr emissions	6720 GBq/year	
¹³⁴ Cs emissions	0.080 GBq/year	
¹³⁷ Cs emissions	0.071 GBq/year	
¹³³ Xe emissions	18,666.7 GBq/year	
Population Density [33]		
Population Density = 1129/km ²		
Impact	Specific risk factors [cases per man Sv]	Specific economic values [\$]
Fatal cancer	0.05	218.26
Nonfatal cancer	0.12	237.6
Specific hereditary effect	0.01	7143.91
Food production [38]		
Food	Export share [%]	Production [tons/year]
Beef	0	1454.1
Chicken	0	256.2

3. Results and Discussion

The results are divided into two sections because two methods were applied in this study. The first section discusses the optimization of the energy mix to meet the future electricity demand without constraints on CO₂ emissions and the environmental impacts of fossil power plants and hydropower plants. The second section discusses the optimization of the energy mix to meet the future electricity demand with constraints on CO₂ emissions and the environmental impacts of NPPs.

3.1. First Scenario (No Carbon Dioxide Emission Constraints)

In this scenario, gas and oil power plants are the predominant sources of electricity that meet the future electricity demand. Hydropower, solar, and wind power plants have a low contribution to the energy mix. There is no contribution from NPPs. The energy supply system reflects the current existing energy policy for the country where oil and gas are the country's major energy resources. Figure 4 demonstrates the optimal electricity generation from different technologies concurrent with future electricity demand. The results show that oil is the optimal choice of electricity generation from 2016 to 2045 and gas is the optimal choice of electricity from 2046 to 2060. When the Egbin fossil power plant is in normal operation, the numbers of cases of health impacts for individuals affected annually as a result of emissions of PM₁₀, SO₂, and NO₂ are 0.387, 0.860, and 4.883, respectively

(Figure 5a). This indicates that more individuals are exposed to nitrate pollutants than to particulate matter (PM) and oxides of sulfur (sulfate). The damage costs owing to the health effects experienced by people as a result of exposure to pollutants and PM, sulfur oxides, and nitrogen oxides are \$701.26, \$6224.68, and \$351.76, respectively during the operation of the Egbin fossil power plant (Figure 5b). These damage costs are equivalent to the costs required for treatment of health effects resulting from exposure to emitted gaseous pollutants.

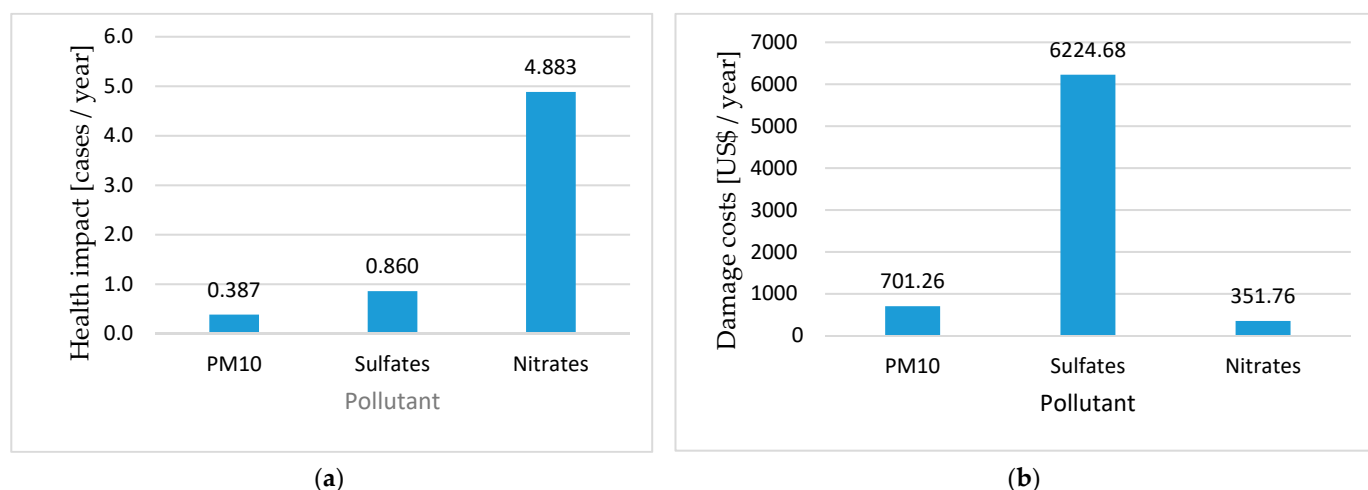


Figure 5. Environmental impacts and damage costs of the Egbin fossil power plant (FPP) in Nigeria. (a) SIMPACT results showing the number of cases per year affected by pollution from Egbin FPP. (b) SIMPACT results showing damage cost resulting from pollution generated by Egbin FPP.

The environmental impacts of the Jebba hydropower plant were calculated using the SIMPACTS code. Although the Jebba hydropower plant is an example of renewable energy, it also has an impact on the environment. Table 6 summarizes the physical impacts that result from the normal operation of the Jebba hydropower plant. Table 6 presents a loss of 311.5 km², 35 km², and 3.5 km² of forest, farmland, and other types of land during the installation and operation of the Jebba hydropower plant, respectively. CO₂ is a highly emitted pollutant, followed by GHG (in carbon equivalent) and CH₄ during the normal operation of the Jebba hydropower plant. These findings suggest that the Jebba hydropower plant's operation may be contributing to global warming. The external damage costs of the Jebba hydropower plant are 846.6 \$per MWh for land loss 782.8 \$per MWh for displacement of people, and 1587 \$per MWh for GHG emissions. These costs are the funds the operator must pay for compensation of damages owing to the deployment and operation of the Jebba hydropower plant. The emission of gaseous pollutants during plant operation presents the highest damage cost.

Table 6. SIMPACTS results showing the physical impacts and damage cost from Jebba hydropower plants in Nigeria.

Parameter	Item	Values	Damage Cost (\$/MWh)
Loss of Land (km ²)	Forest	311.5	846.6
	Farmland	35	
	Other land	3.5	
	Total	350	
Displacement and Resettlement (persons)	Displaced persons	28,875	782.8
	Resettled persons	17,325	
Emissions (tons/year)	CH ₄ (Mean)	6300	1587
	CO ₂ (Mean)	629,300	
	GHG (in carbon equivalent)	207,709	

3.2. Second Scenario (with Carbon Dioxide Emission Constraints)

In this scenario, it was assumed that NPP technology was an alternative solution for Nigeria to meet its future electricity demand and was a solution to reduce CO₂ emissions. Figure 6 shows the energy mix required from all power plants to meet the future demand. It clearly demonstrates that oil and gas contributions to electricity production were limited, and nuclear energy contributed the highest percentage to electricity generation. This is attributed to the efforts made to reduce CO₂ emissions, as assumed in this scenario.

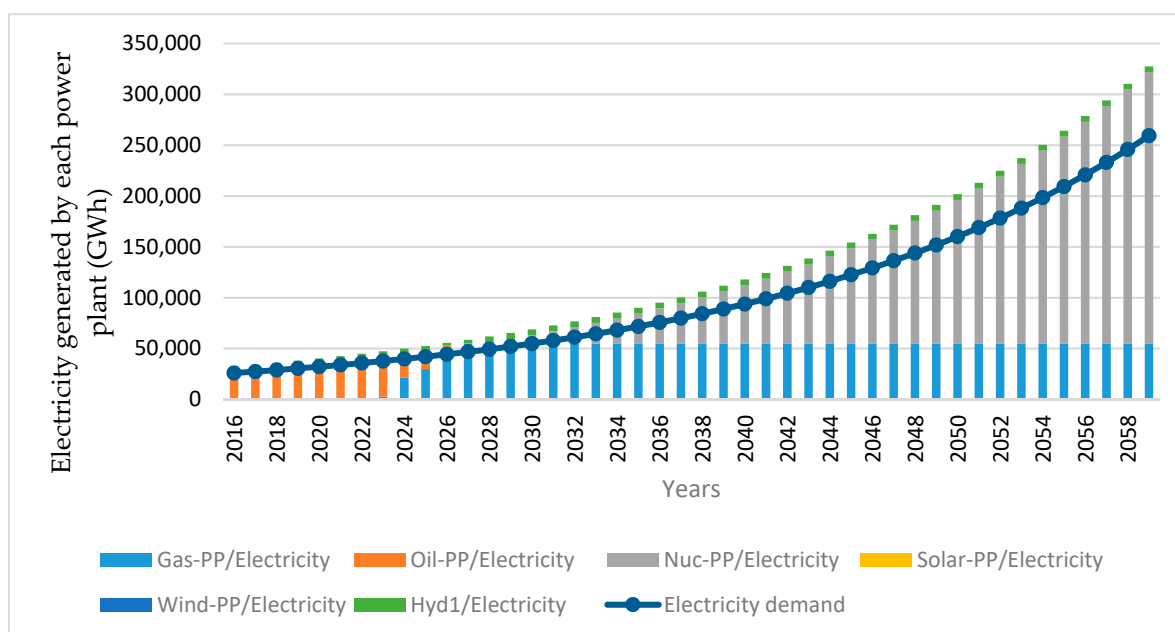


Figure 6. Increase in electricity production and demand from all power plants with limit on CO₂ emission using MESSAGE code for the modeling period under study.

Table 7 comparison between the contributions of each power plant in both scenarios. In the first scenario, the contribution of oil power plant is 81% in 2016 and increased until 100%, whereas in the second scenario, the contribution of oil power plant is 81% and decreased to 32%. The contribution of gas power plant in the first scenario is 0.0% in 2016 and increased to 97% to replace the contribution of oil, whereas in the second scenario, the gas power plant contributes 57% in 2025 and decreased to 17% in 2059. The Nuclear power plant has not contribution in the first scenario, whereas in the second scenario, the nuclear power plant substitutes the oil and gas production. The contribution of nuclear power plant started in 2030 with 11% and increased to 81.5% in 2059.

Table 7. Percentage (%) contribution of electricity from each power plant with and without CO₂ constraint.

Year	Without CO ₂ Constraint (Scenario 1)						With CO ₂ Constraint (Scenario 2)					
	Gas-PP	Oil-PP	Nuc-PP	Solar-PP	Wind-PP	Hyd-pp	Gas-PP	Oil-PP	Nuc-PP	Solar-PP	Wind-PP	Hyd-pp
2016	0.00	81.11	0.00	0.34	1.09	17.46	0.00	81.11	0.00	0.34	1.09	17.46
2020	0.00	84.77	0.00	0.27	0.88	14.08	0.00	91.12	0.00	0.27	0.88	7.73
2025	0.00	88.51	0.00	0.21	0.52	10.76	56.63	31.89	0.00	0.21	0.52	10.76
2030	0.00	91.40	0.00	0.16	0.21	8.23	79.83	0.00	10.96	0.16	0.21	8.84
2035	0.00	93.59	0.00	0.12	0.00	6.29	61.01	0.00	32.59	0.12	0.00	6.29
2040	0.00	95.20	0.00	0.00	0.00	4.80	46.62	0.00	48.57	0.00	0.00	4.80
2045	0.00	100.0	0.00	0.00	0.00	0.00	35.63	0.00	60.70	0.00	0.00	3.67
2050	97.19	0.00	0.00	0.00	0.00	2.81	27.23	0.00	69.96	0.00	0.00	2.81
2055	97.86	0.00	0.00	0.00	0.00	2.14	20.81	0.00	77.05	0.00	0.00	2.14
2059	98.27	0.00	0.00	0.00	0.00	1.73	16.78	0.00	81.49	0.00	0.00	1.73

The environmental impacts of the proposed Geregu NPP in Nigeria during normal operation were estimated using SIMPACTS software. Figure 7a shows 0.014, 0.033, and 0.003 cases of fatal cancer, nonfatal cancer, and specific hereditary effects, respectively,

because of the normal operation of the proposed Geregu NPP. This implies that the number of health impact cases from the NPP is lower than that from fossil fuel plants. Figure 7b shows the annual damage costs of \$4.731, \$12.360, and \$30.968 for fatal cancer, nonfatal cancer, and specific hereditary effects, respectively. The annual damage cost is the cost caused by health impacts resulting from radionuclide emissions per year during the normal operation of the proposed Geregu NPP. This implies that the damage cost of fossil power plants is higher than that of NPPs.

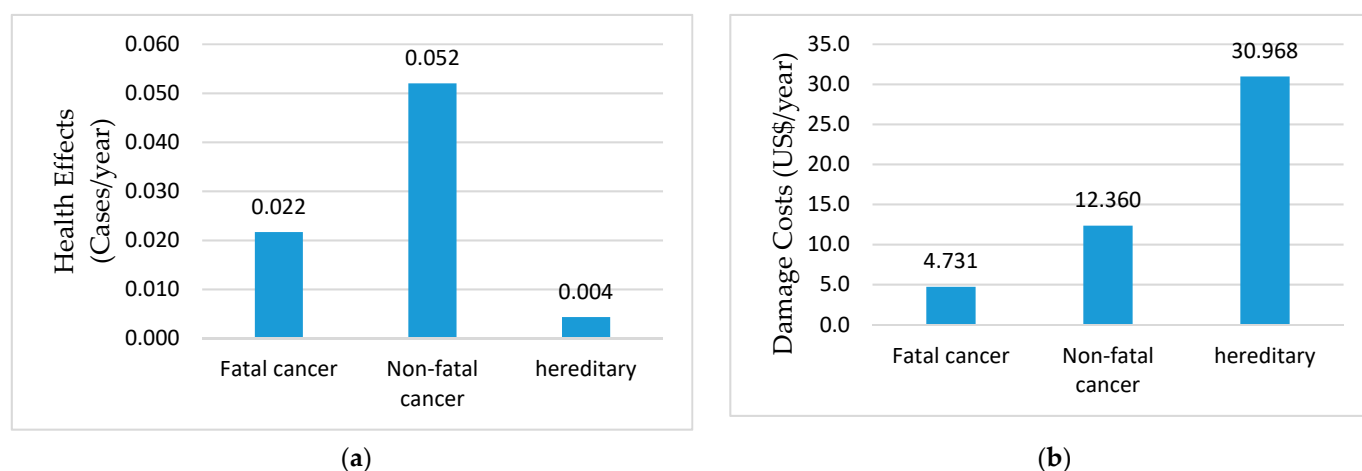


Figure 7. Health impacts and damage costs of the proposed Geregu NPP in Nigeria. (a) SIMPACT results showing various health effects from the released of radioactive materials during normal operation per year. (b) SIMPACT results showing damage cost resulting from radioactive materials released during normal operation per year.

4. Conclusions

Nuclear energy is regarded as one of the cleanest sources of energy due to its low greenhouse gas emissions, baseload power with a consistent and massive output. Unlike other low carbon renewable energies such as solar, wind, and hydro, nuclear is regarded as a reliable source of energy. However, following the Chernobyl disaster in 1986, the radiophobia regarding the use of nuclear power plant increased and many countries implemented reactor shutdowns, while others see nuclear energy as a valuable alternative to meet their energy needs. The public perception is very important in acceptance of any nuclear program. To achieve this, public awareness in terms of environmental impacts and economic benefits compared to other electricity generation technologies such as fossil and hydro power plants is key. This study introduces the nuclear power plant as a best choice for Nigeria electricity generation technology not only to meet the final electricity demand in Nigeria's future energy mix but also to protect the environment against the effect of climate change by reducing carbon emission. Previous literature discussed the nuclear power plant from the viewpoint of optimal energy mix in Nigeria to meet its future demand. In this study, we evaluated the best choice of technology that can be used to generate electricity based on two criteria, cost and environmental impact.

The MESSAGE code was employed to model two case scenarios of the energy supply system in Nigeria to find appropriate alternative power technologies that can be applied to meet long time energy need therefore reducing CO₂ emissions. The first scenario was modeled with no CO₂ emission restrictions, whereas in the second scenario, CO₂ emission restrictions were assumed. The SIMPACTS code was used to estimate the environmental effects and damage costs resulting from normal operation of electricity generation technologies in Nigeria. The electricity generation technologies modeled in SIMPACTS included the following: the Jebba hydropower plant, the Egbin fossil fuel power plant, and the proposed Geregu NPP. The results from MESSAGE showed that oil and gas power plant technologies are the optimal sources of electricity supply with no limits on CO₂ emissions. Currently, wind, solar, and hydro technologies contribute the lowest percentages to Nigeria's energy

mix. Gas technology is currently the most predominant source of electricity in Nigeria. With limits placed on CO₂ emission in line with the Paris agreement of 2015, gas and nuclear technologies are the optimized electricity-generating technologies contributing to Nigeria's energy mix in the future due to its growing population. Result from SIMPACTS computer code shows that NPPs have the lowest total damage costs, whereas fossil fuel power plants have the highest total damage costs. This study concluded that an NPP is the most environmentally friendly technology, given the fact that it has the lowest environmental impacts during normal operation and the lowest damage costs. Conversely, fossil fuel technologies impose a high burden on the environment in terms of damage cost and health impacts. Based on these results, nuclear power is the best choice for electricity generation technology to achieve the final energy needs in Nigeria's future energy mix. The constant growth rate used in this study was based on the rapid population growth in the country.

The major drawbacks of various electricity generation technologies such as nuclear energy are mainly nuclear accidents and management of radioactive waste from the operation of nuclear power plants. The release of radioactive materials during nuclear accidents has resulted in adverse effects including death to the members of the public which increases the radiophobia of nuclear energy. Additionally, the management of radioactive waste arising from the operation of nuclear power plants constitutes long time effects on the sustainability of the environment due to limited radioactive waste management disposal facilities and its associated longer decay period. According to the US energy information 2019, fossil, hydro, wind, and solar cannot meet future electricity demand due to low generation capacity of 56.8%, 39.1%, 34.8%, and 24.5% respectively, whereas nuclear has a maximum generation capacity of 93.5% which is nearly double that of renewable sources and three times that of wind and solar. Fossil fuel is the major source of carbon emission and becomes depleted over time. A hydropower plant has a greater consequence on the environment and agricultural products due to flooding from the reservoir which results displacement of homes, loss of life, and damage to farmland and agricultural products. Wind is inconsistent and can blow at various speeds, therefore, it is hard to predict the amount of energy it can produce. Solar energy cannot produce electricity during the night and when there is no sun, power has to be stored in a form of battery to ensure consistent supply. Presently in Nigeria, fossil power plants accounts for 83% contribution of electricity sources, hydropower accounts for 16%, while wind and solar energy accounts for 1%, respectively. Conclusively, nuclear energy is recommended to be part of Nigeria's energy mix to reduce the CO₂ emissions since other low carbon emission electricity generation technologies such as solar, wind and hydro does not have the capacity to attain the future electricity needs in Nigeria due to high population growth rate. Findings from this study will serve as a reference point for modeling long-term energy mix and reducing CO₂ emission in Nigeria.

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References

1. Ministry of Energy. *Country Report on Nigeria Energy System*; Ministry of Energy: Asaba, Nigeria, 2015; pp. 1–34.
2. Statista. Nigeria: Gross Domestic Product (GDP) in Current Prices from 1996 to 2026. Available online: <https://www.statista.com/statistics/383118/gross-domestic-product-gdp-in-nigeria/> (accessed on 17 June 2021).
3. Macrotrends. Nigeria GDP per Capita. 2019. Available online: <https://www.macrotrends.net/countries/NGA/nigeria/gdp-per-capita> (accessed on 17 June 2021).
4. *British Petroleum (BP) Statistical Review of World Energy*, 70th ed.; Whitehouse Associate: London, UK, 2021; pp. 1–72.
5. US Energy Information Administration. *Country Analysis Executive Summary: Nigeria*; Independent Statistics & Analysis: Washington, DC, USA, 2020; pp. 1–10.
6. Climate Transparency. *Nigeria's Climate Action and Responses to the COVID-19 Crisis*; Climate Transparency: Nigeria, 2020; pp. 1–20. Available online: <https://www.climate-transparency.org/wp-content/uploads/2021/01/Nigeria-CT-2020.pdf> (accessed on 17 June 2021).
7. Sambo, A. *Matching Electricity Supply with Demand in Nigeria*; International Association of Energy Economics, 2008; pp. 32–36. Available online: <https://www.iaee.org/documents/newsletterarticles/408sambo.pdf> (accessed on 17 June 2021).
8. Foundation, S.; Intelcap. *Mapping the Off-Grid Solar Market in Nigeria*; Intelcap: Nigeria, 2019; pp. 1–56. Available online: <https://www.assets.signify.com/is/content/Signify/Assets/signify/global/20201105-mapping-the-off-grid-solar-market-in-nigeria-2019.pdf> (accessed on 17 June 2021).
9. Abdullahi, K.; Roh, M.-S. Long Term Energy Plan for Nigeria using Message Code for Energy Optimization. *Int. J. Eng. Res. Technol. (IJERT)* **2016**, *5*, 11. [CrossRef]
10. Kichonge, B.; John, G.R.; Mkilaha, I.S. Modelling energy supply options for electricity generations in Tanzania. *J. Energy S. Afr.* **2015**, *26*, 41–57. [CrossRef]
11. Batmunkh, T.; Roh, M.S. *Long Term Energy Plan of Mongolian with Nuclear Power Plant Using Message Code*; Korean Nuclear Society: Jeju, Korea, 2014.
12. Liun, E.; Kuncoro, A.H.; Sartono, E. Environmental impacts assessment of Java's electricity generation using SimPacts model. In Proceedings of the International Conference on Advances in Nuclear Science and Engineering in Conjunction with LKSTN; 2007. Available online: https://digilib.batan.go.id/e-prosiding/Icanse/article/D3.5-Edwaren_Environmental.pdf (accessed on 17 June 2021).
13. Liun, E. Optimum Solution Expectation on Sumatra Electricity Expansion Planning Beyond 2030 Using WASP-IV Package. In Proceedings of the International Conference on Advances in Nuclear Science and Engineering in Conjunction with LKSTN; 2007. Available online: https://digilib.batan.go.id/e-prosiding/Icanse/article/D3.3-Edwaren_Optimum.pdf (accessed on 17 June 2021).
14. Macías, P.; Islas, J. Damage costs produced by electric power plants: An externality valuation in the Mexico City Metropolitan Area. *Sci. Total Environ.* **2010**, *408*, 4511–4523. [CrossRef] [PubMed]
15. Ali, H.; Alsamaoal, A.; Seif Aldin, S. Estimating the health damage costs of Syrian electricity generation system using impact pathway approach. *Energy* **2010**, *35*, 628–638.
16. IAEA. *Nuclear Power Reactors in the World*; International Atomic Energy Agency: Vienna, Austria, 2021.
17. Johan, A.B.C.; Davide, B.; Antonio, C.; Guglielmo, L.; Mario, M. Lattice Boltzmann Method Applied to Nuclear Reactors—A Systematic Literature Review. *Sustainability* **2020**, *12*, 7835.
18. Ewim, D.R.E.; Oyewobi, S.S.; Dioha, M.O.; Darajimba, C.E.; Oyakhire, S.O.; Huan, Z. Exploring the perception of Nigerians towards nuclear power generation. *Afr. J. Sci. Technol. Innov. Dev.* **2021**, 1–12. [CrossRef]
19. IAEA. *Modelling Nuclear Energy Systems with MESSAGE: A User's Guide*; International Atomic Energy Agency: Vienna, Austria, 2016.
20. International Institute for Applied Systems Analysis. MESSAGE Core Formulation. 2021. Available online: https://docs.messageix.org/en/stable/model/MESSAGE/model_core.html#constraints-on-resource-extraction (accessed on 26 July 2021).
21. IAEA Agency. *Model for Energy Supply Strategy Alternatives and Their General Environmental Impacts (User Manual)*; International Institute for Applied Systems Analysis: Laxenburg, Austria, 2017; pp. 1–346.
22. Schrattenholzer, L. *The Energy Supply Model MESSAGE*; International Institute for Applied Systems Analysis: Laxenburg, Austria, 1981.
23. Kelechi, O.; Iladare, O.; Ajiinka, J.A.; Dosunmu, A.; Ibe, A.C. *Estimating Fair Market Value of Nigerian Petroleum Assets: A Risk-Based Approach*; OGEL, 2021; ISSN 1875-418X. Available online: <https://www.ogel.org/journal-advance-publication-article.asp?key=672> (accessed on 26 July 2021).
24. US Energy Information Administration. Nigeria Electricity Consumption. 2018. Available online: <https://www.eia.gov/international/data/country/NGA/electricity/electricity-consumption?pd=2&p=0000002&u=0&f=A&v=mapbubble&a=-&i=none&vo=value&t=C&g=none&l=249--157&s=315532800000&e=1546300800000> (accessed on 17 June 2021).
25. US Energy Information Administration. *Capital Cost and Performance Characteristic Estimates for Utility SCALE Electric Power Generating Technologies*; US Energy Information Administration: Washington, DC, USA, 2020; pp. 1–12.
26. Jorli, M.; Van Passel, S.; Sadeghi, H.; Nasser, A.; Agheli, L. Estimating Human Health Impacts and Costs Due to Iranian Fossil Fuel Power Plant Emissions through the Impact Pathway Approach. *Energies* **2017**, *10*, 2136. [CrossRef]

- [illegible]