

# Innovations

## Nuclear Energy Development Research in Nigeria: A review

<sup>1,2</sup>Festus O. Abayomi; <sup>3</sup>Charles C. Ajaero & <sup>4</sup>Kenneth C. Onyeaka

<sup>1</sup>Department of Engineering, Nuclear Science and Engineering, North-West University, Potchefstroom Campus, Potchefstroom, South Africa

<sup>2</sup>Nigerian Nuclear Regulatory Authority (NNRA)

<sup>3</sup>Center for Environmental Management and Control, University of Nigeria, Enugu, Nigeria

<sup>4</sup>Department of Electrical/ Electronic Engineering, Enugu State University of Science and Technology, Enugu

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**Abstract:** *Nigeria, a developing country with huge population increase is facing energy crisis. Thus, to meet energy demand, the country has committed to building a nuclear power plant (NPP). This review aims to systematically evaluate research evolution and issues with NPP in Nigeria. Peer reviewed journal publications were accessed from Google Scholar and SCOPUS databases. They were identified, screened and evaluated using set inclusion- exclusion criteria. Among the included studies, 23.5% are 'Review' articles, while 76.5% are 'Research articles'. Different aspects of issues related to deployment of NPP were identified. Majority (47%) dealt with potential of NPP electricity generation and its emission mitigation. 35.3% dealt with environment and safety issues of NPP, including atmospheric dispersion (normal operation and accidental release) and seismicity; while 17.7% focuses on resources including human resources development, technical, political, financial and others. 92.3% of the corresponding or lead authors are affiliated or have other affiliations with foreign universities, almost all of which have operational NPP. South Africa accounts for 38.5% and India, 15.4% of the authors' foreign affiliations. This indicates the need for Nigerian researchers to collaborate with those in nuclear advanced countries.*

**Keywords:** *Nuclear; power; energy production; sustainability; Nigeria.*

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### Introduction

Decarbonization of energy production is critical for 2015 Paris Agreement. Electricity supply and GHG emissions are strongly associated, and are among major issues facing Nigeria (Okafor et al, 2022, Ajaero et al, 2023). Nigeria pledged in its Nationally Determined Contributions (NDC) to decrease emissions by 47% below

BAU by 2030. Following this, the country passed the Climate Change Act (CCA) to support greenhouse emissions reduction, cleaner and sustainable growth. Further, Nigeria Energy Transition Plan (ETP) in August 2022, was rolled out to reach net-zero or carbon neutrality target by 2060. The ETP calls for “expansion of gas generation capacity to establish baseload capacity for meeting increased electricity demand and integrating renewables” (Nigeria Energy Transition Plan, 2022). Although gas is a low-carbon energy source, it is not net-zero or carbon neutral. On the other hand, nuclear is a reputed net-zero energy system (Price et al, 2023; Dehner et al, 2023). A panel data using EKC model and comprising 18 countries with nuclear reactors showed that 1% increase in nuclear power decreases per capita CO<sub>2</sub> emission by 0.26-0.32% between 1970 to 2015 (Lee et al, 2017). Globally, around 1.2–2.4 Gt CO<sub>2</sub> emissions that would have been produced by coal or natural gas combustion are avoided each year by NPP. To achieve the 2°C target stated in the Paris agreement, NPP capacity must increase to about 930 GW by 2050. The investment will cost around \$4 trillion (Prävãlie and Bandoc 2018). At 26 tCO<sub>2</sub>/ GWh each, only wind and hydro have better life-cycle CO<sub>2</sub> emission compared to nuclear (29 tCO<sub>2</sub>/ GWh). For other sources, they are as follows – natural gas (499 tCO<sub>2</sub>/ GWh), solar PV (85 tCO<sub>2</sub>/ GWh), biomass (45 tCO<sub>2</sub>/ GWh) (Adewuyi et al, 2020).

Renewables such as bioenergy, solar, wind and hydro (VREs) are important for Nigeria future sustainable energy mix (Okafor et al, 2021). However, bioenergy (especially 1<sup>st</sup> generation) impacts the natural ecosystem and the environment (Dioha et al, 2019) and also creates food versus energy conflict which is critical for a developing country like Nigeria (Okafor et al, 2022). Solar, wind and hydro are challenged with intermittency related to meteorological issues, which lead to periods of low-energy production. In late summer and winter, short-days length of solar irradiation leads to the 7 and 14- days low production (van der Wiel et al, 2019). Variations in daily and seasonal wind speed also affect its energy production and load demand (Solaun and Cerda, 2019). Storage offers a means to solve the issue of their intermittency. However, the huge cost of battery storage (\$300/ kWh) negates its cost efficiency. Also, the utilization of such batteries negates the environmental rationalization for this type of renewable energy technology. Manufacture and disposal of the super-batteries adversely impacts the environment (Salakhedinov and Agyeno, 2020). Thus, the importance of integrating nuclear in Nigeria’s future cleaner energy mix, to offset intermittency and provide frequency stability. Nuclear power has a stable base load electricity supply (Aliyu et al, 2013).

Accordingly, the purpose of this study. The aim of this study is to review relevant works done on nuclear energy so as to contribute to policy and decision making toward pursuing nuclear energy. The study objectives of the review are:

- To identify how included publications in the area has evolved and
- To identify and discuss the thematic issues raised in the included literature.

**Materials and Methods**

Secondary research method was used for the study, and comprised three stages- literature search, eligibility criteria and selection.

**Literature search**

Search was conducted on SCOPUS and Google Scholar on February 9 2023, using pertinent keywords - "Nuclear" OR "Nuclear power" OR "Nuclear Energy" AND "Nigeria". SCOPUS search gave 648 documents. After Okon et al (2021), notes, book chapters and conference papers were excluded, since most of them are not peer-reviewed. The unrefined search yielded studies done in other countries. Therefore, country or territory of study was limited to Nigeria. This yielded a total search of 105. Search on Google scholar using the Boolean keywords gave initial record of 380,000. To Limit the search to a manageable and relevant dataset, Google scholar 'Advanced Search' was used, and the following conditions, find articles: (i) with all of the words "Nigeria"; (ii) with at least one of the words "Nuclear" "Nuclear power" "Nuclear Energy" and (iii) where my words occur 'in the title of the article'. The refinement yielded a total of 78 which are relevant to the study objectives.

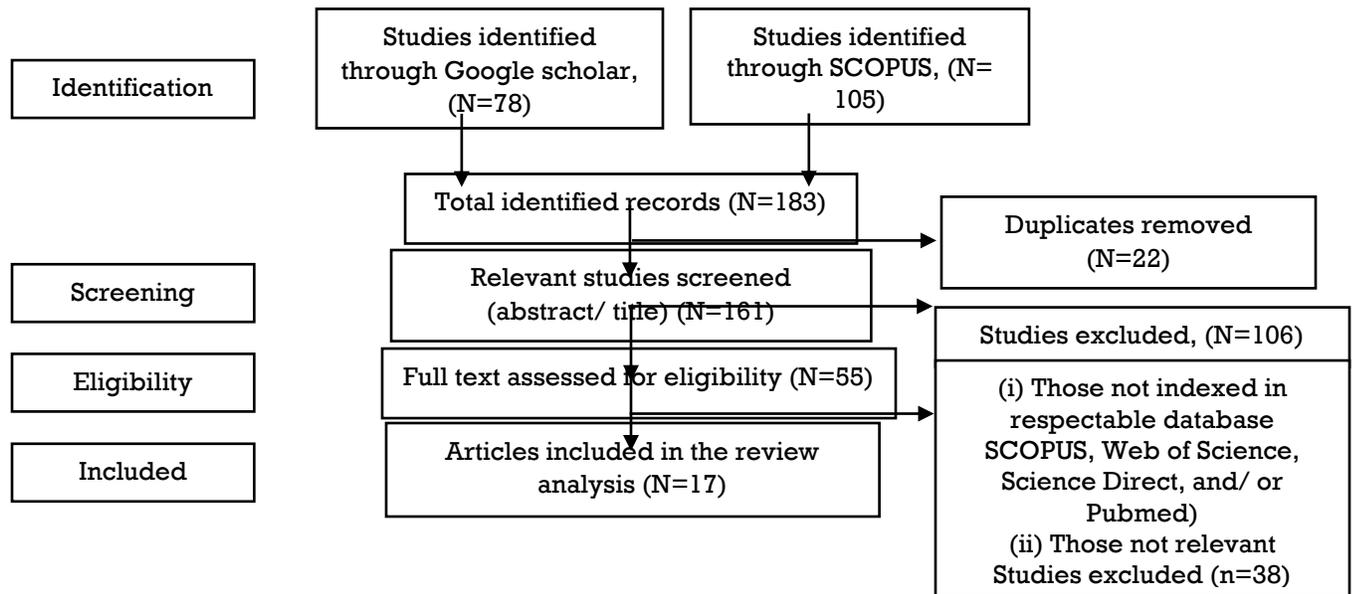


Figure 1: Flow chart for the literature selection (after Okon et al, 2021)

**Eligibility**

Studies evaluated for inclusion were required to meet some specific criteria related to nuclear energy in Nigeria. They are:

1. Inclusion of papers that discusses nuclear power plant, whether energy generation, environmental, modeling, geographic location, etc;
2. Exclusion of papers that discusses nuclear or reactor core physics;
3. Exclusion of papers that discusses radioactive level from any other natural or human activities that does not involve normal or accidental release from NPP; and
4. Inclusion of papers that comprises nuclear energy together with other renewable energy options for Nigeria.

**Study selection**

After duplicates which were twenty-two in number were removed, screening was then conducted for the 161 studies remaining. After going through the titles and abstracts only, 106 documents were removed. Full text assessment was conducted on the remaining 55 studies using set eligibility criteria. 38 papers were removed, while 17 papers were included in the review.

**Result**

**Publication evolution**

The search result, and the application of inclusion – exclusion criteria yielded a total of seventeen articles.

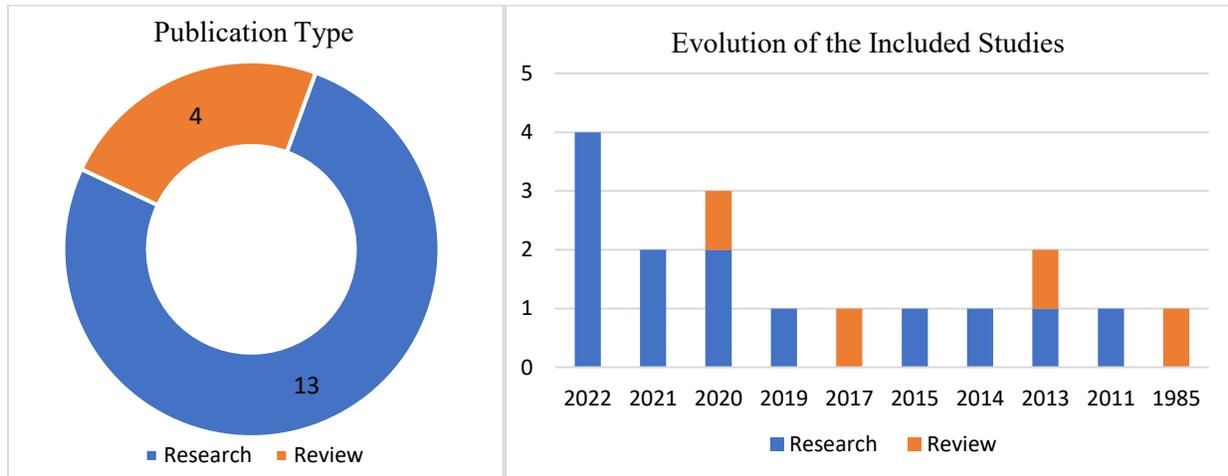


Figure 2: Evolution of publication by type and years

Among the included studies, 23.5% are ‘Review’ articles, while 76.5% are ‘Articles’. The earliest identified publication in our included studies was 1985, while the latest was the year 2022. There have been infrequent and erratic publications on nuclear regarding the purpose of energy generation. From 1986 to 2010, no paper was identified in our dataset. The year 2020 to 2022 accounts for more than half (52.8%) of the identified publications in our dataset. This indicates growing interest in nuclear energy in Nigeria. Excluding the year 2013 (which recorded 3 papers or 17.6% of the included studies), the other years recorded only one paper each. Fourteen sets of authors authored the 17 included papers.

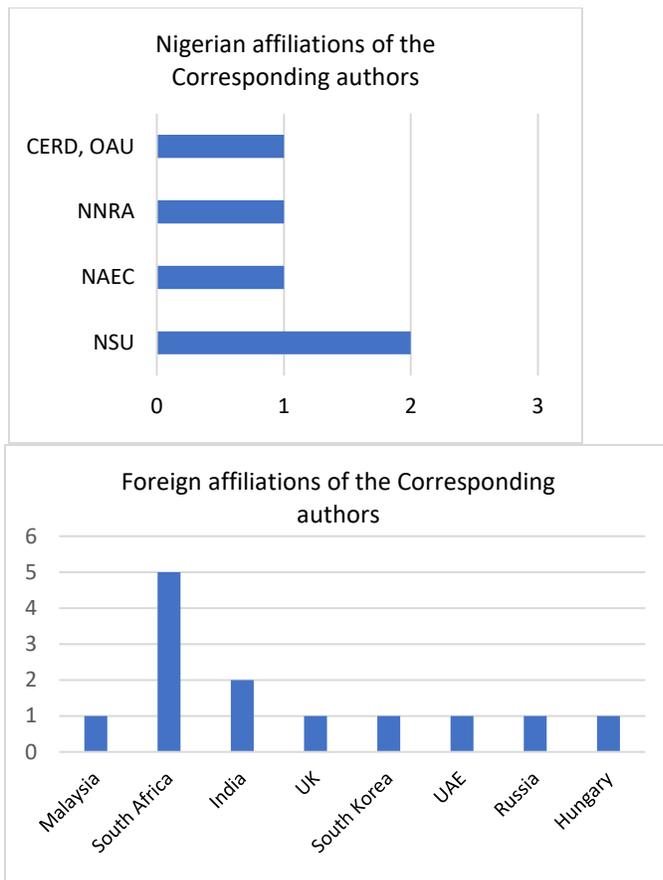


Figure 3: Affiliations of the Corresponding Authors

All the foreign affiliations (countries) operate a nuclear power, except Malaysia. UAE’s Barakah NPP started in 2019 was commissioned around 2022. 92.3% (12/13) of the foreign affiliated countries have nuclear power. Excluding NSU (Nasarawa State University), the other local affiliations are Nuclear or energy-related such as Centre for Energy Research and Development (CERD), Obafemi Awolowo University, NNRA (Nigerian Nuclear Regulatory Authority) and NAEC (Nigerian Atomic Energy Commission). This buttresses the importance of collaborating with foreign

institutions to foster nuclear science research for both nuclear advancement and policymaking for Nigeria.

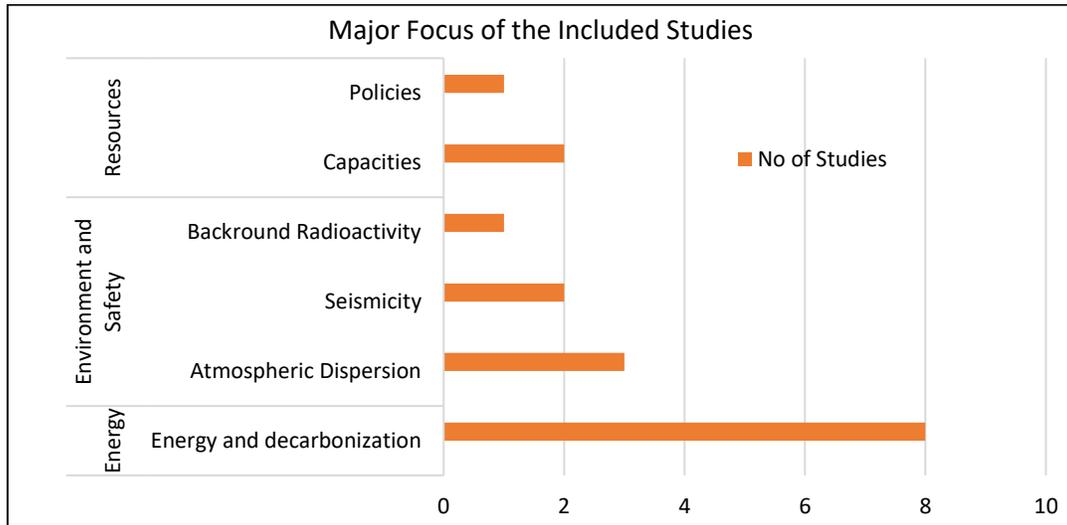


Figure 4: Major Focus of the Included Studies

From figure 4, majority (47%) of the included studies focused on nuclear energy as a source of providing low-carbon energy, which will help reduce emissions in the power sector while also increasing energy generation while also. Three (17.6%) of the included studies dealt with atmospheric dispersion from normal operation and accidental release (Aliyu et al 2013; 2014 and 2015); while two articles (11.8%) studied seismicity mapping and Probabilistic Seismic Hazard Analysis (PSHA) around proposed NPP sites (Eluyemi et al (2020a and 2020b). Two papers (11.8%) centered majorly on capacities – human resource development (Egieya et al, 2022) and others (political, financial, technological, etc) (Jewell, 2011). One ‘Article’ studied background radiation of a proposed site for the NPP (Ekong et al, 2021).

**Identified Issues from the included Studies**

**Low-carbon or sustainable energy**

Nuclear energy is the second largest source of low-carbon electricity in the globe, after hydropower (Salakhedinov and Agyeno, 2020). Nuclear power has a crucial role to play in de-carbonization of Nigerian power sector (Ewim et al, 2021). By 2050, it is projected that nuclear will contribute 8% to Nigeria renewable energy mix (Ibrahim and Ayomoh, 2022). One of the advantages of NPP is low operating costs. For an average NPP, 20-30% of the net operating costs is accounted for by fuel. Comparatively, 80-85% of thermal (gas-fired) power plants are related to fuels (Salakhedinov and Agyeno, 2020). The cost of generating electricity in the U.S. were – coal (2.9 cent/kWh); gas (5 cent/kWh), oil (12.1 cent/kWh) and nuclear (2.03 cent/

kWh) (Aliyu et al, 2013; Vujic et al, 2012). Similarly, simulation done for Nigeria using MESSAGE showed nuclear has the lowest variable cost, at \$2.37 /MWh. Others were gas power plant, GPP (\$6.2/ MWh), wind power plant, WPP (\$10/ MWh) and oil power plant, OPP (\$4.7 /MWh). Compared to GPP which has losses of around 50%, it is 10% for NPP. Nuclear has the highest plant capacity factor, at 0.9. comparatively, it is 0.3 (each for OPP, GPP and HPP), 0.2 (Solar-PP), 0.15 (WPP) (Kim et al, 2021). NPP has the highest lifetime, at 60 years; compared to hydro (40-45 years); solar thermal, incinerator and geothermal (at 30 years each); wind turbine (25 years) and gas turbine (15 years) (Ibrahim and Ayomoh, 2022). The high initial costs for an NPP, lengthy construction periods, deferred return on investments (ROI) and the tendency of such venture to cost overruns in unclear regulatory environment; funding NPP will requires innovative instruments in Nigeria (Ejiogu, 2013). Recent estimates show the cost of constructing a NPP is \$4000/ kWe (or \$ 4 billion per GWe) (Jewell, 2011). The disparity between the growing demand and supply has led to over-dependence on use of fueled generators (Ibrahim and Ayoomoh, 2022). Nigerian spends about \$14 billion per annum on off-grid fossil-fueled self-generation, whereas construction of the 4.8 GW NPP (all phases) proposed is estimated to cost \$20 billion (Salakhetdinov and Agyeno, 2020).

The levelized cost of energy (LCOE) of nuclear fares well with other RE sources, at around \$0.10/ kWh. LCOE for other REs were off-shore wind and solar thermal (\$0.12/ kWh each), biomass (\$0.9/ kWh), natural gas (\$0.065/ kWh), hydro (\$0.035/ kWh), on-shore wind (0.049/ kWh), solar PV (0.046 /kWh) (Adewuyi et al, 2020). Nuclear energy offers better insulation from changes in the price of energy resource (Jewell, 2011). The insulation is critical to energy and national security, as fluctuation in energy prices affects all other sectors of the economic. As noted in Okolo (1985), Egieya et al (2021), Nigeria, has a potential uranium deposit. Even if Nigeria has commercially available uranium ore deposits, or accesses it from neighboring Niger, the cost, power and technical expertise requirement of enriching uranium is high (Okolo, 1985). Developing enrichment facilities however, will provide energy security as it guarantees energy independence and supply diversity (Jewell, 2011).

Nigeria is far from reaching basic IAEA recommendation for construction and operation of an NPP. The IAEA proposes that no single NPP should comprise more than 5-10% of a country's total installed grid capacity (Ejiogu, 2013). This means that Nigeria's electricity grid should be more than 10,000 MW. Total installed transmission capacity of Nigeria is around 7500 MW. Because of these technical factors, Nigeria was categorized as having 'low technical capacity' together with other fifteen countries who are interested in siting NPP (Jewell, 2011).

## **Human Resources Development**

IAEA milestone methodology include Human resource development (HRD) as one of the nineteen structural concerns to be addressed before implementation of NPP. HRD for NPP is especially demanding for Nigeria because of the specialized labor force necessary for nuclear reactors. It will take about 10 years to develop some of the required skills (Egieya et al, 2022). This is recognized in Nigeria's Nuclear Roadmap of 2007. The first of the three phases, established in the Roadmap is human capital development and capacity building. As far back as the 80's the issue of manpower or human resource geared towards developing and running of NPP have generated concern (Onyejekwe, 1981). To develop capacity, three nuclear research and training centres was established in Nigeria. This has led to human capital development, though the significance of the contribution in terms of development, application and effective operation of nuclear technology is uncertain. The centers are Center for Energy Research and Development (CERD) at Obafemi Awolowo University, Ile-Ife and Center for Energy Research and Training (CERT) at Ahmadu Bello University, Zaria – both in 1978 and the Nuclear Technology Centre (NTC), Abuja, in 1988 (Ejiogu, 2013). It is estimated that around 9045 personnel are required prior to commissioning of NPP in Nigeria by 2033(Egieya et al, 2022).

To train local nuclear professionals, Nigeria has contracted with 11 local universities and polytechnics, to implement nuclear science and engineering curriculum up to postgraduate levels (Egieya et al, 2022). The different nuclear research centers are boosting nuclear reactor research, contributing to expertise and knowledge transfer which is critical for NPP design and operation. For example, the NIRR-1 which began operation in 2004 was able to convert high-enriched uranium (HEU) fuel to low-enriched uranium (LEU) fuel reactor (Brimmo et al, 2017). Some of the important published works carried out at the various research centers include Monte Carlo simulation of nuclear reactor parameters (Jonah et al, 2007); reactor power characteristics because of changes in core-coolant temperature (Ahmed et al, 2008); possibility of low-enrichment uranium fuels for MNSR conversion (Jonah et al, 2009). Similarly, through NAEC, Nigeria is looking into possible partnership with institutions like the National Power Training Institute of Nigeria (NAPTIN) to train and educate technicians and craftsmen (Egieya et al, 2022)

Nigeria has a regulatory authority for nuclear. Nigerian Nuclear Regulatory Authority (NNRA), which was created by Act 19 of 1995, but became operational in May 2001. The NNRA was charged with regulating all nuclear activities, laws and regulations in Nigeria (Ewim et al, 2021). The NNRA has gained more than 10 years' capability in maintaining good practices of regulating safe and sound operation of the NIRR-1 (Egieya et al, 2021). Expectedly, this will be widened to the regulation of

NPP. Further, standards and regulations for the instruction and training of workforce together with operators of NPP are at conclusion stage (Egieya et al, 2021). Although Nigeria has the necessary pre-requisite regulatory framework for NPP development, the possession of actual equipment, technical expertise and manpower to operate NPP safely is lacking (Ejiogu, 2013). International collaboration or agreement and its implementation is critical to developing or transferring capacity building to Nigeria. A typical example of such is the three agreements Nigeria signed with Russia Federation namely (i) Inter-Governmental Agreements, including Cooperation on the Development of Nuclear Energy for Peaceful Uses (2009); (ii) Cooperation in the Design, Construction, and Decommissioning of Nuclear Power Plant(s) in the Federal Republic of Nigeria (2012) and (iii) Cooperation in the Construction of a Multi-Purpose Research Reactors (MPRR) Complex (2016) (Egieya et al, 2022).

## **Safety and Security**

### **Atmospheric dispersion**

Atmospheric dispersion is the major means for transport and deposition of radioactive materials from NPP in event of failure, accidents or seismological events. The health implications of radioactive release in case of such scenarios depends on meteorological factors such as wind speed, wind direction, rate of precipitation and atmospheric stability. These are critical factors considered in siting of NPP (Aliyu et al, 2013). Assessment in Nigeria shows that level of radioactivity in locations where there are no radiological human activities are lower or within the global average level, while locations where radiological human activities are established is likely to have higher levels (Ekong et al, 2021). Small amount of carbon-14 ( $^{14}\text{C}$ ) are produced during normal operations of NPP. The occurrence is because of neutron capture in Light Water Reactor (LWR). The element is emitted in two forms – oxides  $^{14}\text{CO}_2$  and in reduced form,  $^{14}\text{CH}_4$  (Aliyu et al, 2013). Generally, the release of  $^{14}\text{C}$  and others during normal NPP operation is highly controlled and fairly below the regulatory standard (Aliyu et al, 2013; Aliyu et al, 2014). The risk quotients (RQs) of normal operation of NPP, i.e. the probability of exceeding screening dose value of  $10 \mu\text{Gy h}^{-1}$  is reasonably low (<5%) (Aliyu et al, 2014). About  $0.01 \times 10^{-3} \text{ Bq/m}^3$  (micro Becquerel per cubic meter) of  $^{14}\text{C}$  will be released by normal operation of a proposed Nigerian NPP site (ItuAkwa Ibom State) in Nigeria, taking into consideration the area's meteorological parameters. At 2000 work-hour per annum, annual radiation dose for a staff of the facility is about  $0.16 \times 10^{-10} \text{ mSv}$  (milli Sievert) which is fairly low. The amount is only for  $^{14}\text{C}$  and does not include total radiation dose when other radionuclides released from NPP are considered. It is estimated that in the event of NPP accident, release rates of  $^{14}\text{C}$  will be 3 times order of magnitude than that of normal operations (Aliyu et al, 2013).

In another simulation involving accidental release (representative of Fukushima) and prevailing local climate at a proposed NPP site (Kogi State) in Nigeria, Krypton ( $^{85}\text{K}$ ) shows the highest atmospheric concentrations, ranging from  $3.39 \times 10^{-3} \text{Bq m}^{-3}$  to  $6.64 \times 10^{-3} \text{Bq m}^{-3}$ . Strontium ( $^{90}\text{Sr}$ ) has the least atmospheric concentration, ranging from  $3.66 \times 10^{-9}$  to  $7.17 \times 10^{-9} \text{Bq m}^{-3}$  (Aliyu et al, 2014). Ground level concentration (ground depositions) of Iodine ( $^{131}\text{I}$ ) and Cesium ( $^{137}\text{Cs}$ ) were 8 and 9 times lower in order of magnitude, respectively than that of  $^{85}\text{K}$ .  $^{137}\text{Cs}$  and  $^{131}\text{I}$  are the radionuclides that causes great concern. Inhalation or ingestion of  $^{131}\text{I}$  localizes in the thyroid gland, increasing the risk of thyroid cancer and other thyroid diseases (Aliyu et al, 2015). The computed effective dose and cancer risk 46 km away (Lokoja) from the proposed Geregu NPP site, is 2-3 times that obtained at the NPP site. This is because of the NE wind effect which transports the nuclides away from the NPP (Aliyu et al, 2014). In a SIMPACT simulation, the health impact of normal operation of a NPP was much lower than those of fossil fueled plants. The number of health impacts from fossil fuel electricity plants was higher than that of an NPP, during normal operation (Kim et al, 2021).

### **Human risk**

The most probable risk to NPP implementation in Nigeria is human-related. The human risk includes technical errors, militancy, terrorism, theft and corruption (Ishola et al, 2019). Corruption and misappropriation of funds also affect construction and operation of an NPP (Salakhedinov and Agyeno, 2020), leading to technical errors or poor maintenance culture. More than 46% Nigerians reported Nigeria has a very poor maintenance culture (Ewim et al, 2021). The lax attitude is a major cause of poor performance in Nigeria's electricity industry. Careless maintenance culture manifests in poor reporting, documentation and learning from past cases and accidents (Ishola et al, 2019). Because of these, Nigeria is included together with 4 Southeast Asian, 2 Latin American and 3 MENA (Middle East and North African) countries as having uncertain or unlikely nuclear power development. Despite their strong capacities and motivations, the above countries were found to fall with the lowest quartile of Political Stability Index (PSI) among 52 countries interested in having NPP. PSI is a measure that a government will be overthrown by violent means (Jewell, 2013). Nigeria is one of those with high political instability. Political unrest or volatility occasioned by socio-economic connections, extreme tensions and ethno-religious conflicts underlies fear about nuclear energy in Nigeria (Salakhedinov and Agyeno, 2020). Militancy activities in the Niger Delta to terrorist attacks (by Boko Haram) and others across Nigeria poses a serious risk to development of NPPs (Aliyu et al, 2013; Ewim et al, 2021). Building of NPPs could draw the attention of extremist groups (Salakhedinov and Agyeno, 2020). 66% of Nigerians opined that political unrest and insurgency is a barrier to developing NPP as a possible power

generation in Nigeria (Ewim et al, 2021). Nigeria, Bangladesh and Venezuela have the lowest Government Effectiveness Indicators (GEI) among 52 countries interested in NPP (Jewell, 2011). Corruption is very common in Nigeria. 48% of Nigerians distrust Nigerian government operation of NPP. Widespread corruption and non-inclusion of the public in the decision-making processes towards implementation of the NPP programs are the factors for the distrust (Ewim et al, 2021). Coupled with corruption, there is a likelihood of the terror groups diverting nuclear materials from the facilities to make 'dirty-bombs' (Salakhedinov and Agyeno, 2020). Globally, the change from HEU reactor fuels to LEU under IAEA direction decreases related security and proliferation risks (Brimmo et al, 2017). Nigeria's NIRR-1 currently run on LEU.

### **Seismology**

Improved observation capacities for earthquakes are recording more events in Nigeria (Afegbua et al, 2019). Nigeria and some of its neighboring West African countries are found in seismotectonic zone 1 (magnitude of 6.0 – 6.5) of the African Zonation map. This is one of the fissure areas where potential large magnitude earthquake is likely to occur in the future (Eluyemi et al, 2020a). Because of the large number of small magnitude events in the South-Western Nigeria, it is expected that Peak Ground Acceleration (PGA) will be observed more in the area. Higher values of PGAs are observed in the Northern regions of Nigeria, which is probably due to larger earthquake magnitudes observed there (Afegbua et al, 2019). A recent tremor that occurred across Nigeria indicates the probability of large magnitude earthquake occurring. In the course of a large earthquake event in North-East geographical zone (which the proposed Lau NPP site, Taraba State falls in), hazard is found to occur between the structural periods of 0.00 s and 0.5 s (Eluyemi et al, 2020b). This indicate that first few microseconds of an earthquake events, threats will be great at the ruptured zones, followed by the areas beyond the ruptured zones. Beyond the ruptured zones, the impact will decay rapidly. The greatest hazard level will be noticed at those located near the fault lines (Eluyemi et al, 2020a). Similar probabilistic Seismic Hazard Assessment (PSHA) in Nigeria showed there is high likelihood of small magnitude earthquakes (lower than 5.0) occurring and recurring within 1, 50, 100 and 1000 years. Earthquake with magnitude of 6.0 is expected to occur every 143 years in Nigeria (Afegbua et al, 2019). The location of Nigeria along a major fault lines in the seismically active Gulf of Guinea (Yarwood and Doser, 1989) and the volcanically active Mount Cameroon (Eluyemi et al, 2020a) statistically predicts large earthquakes in the South-Western Nigeria (Adepelumi, 2009).

**Radioactive waste**

Operation of NPP generates nuclear waste in the forms of spent fuels, etc. More than 63% Nigerians believed that radioactive waste disposal is one of the critical barriers to siting NPP in the country (Ewim et al (2022). Radioactive waste disposal is one of the basic factors in selecting nuclear power for electricity generation. Presently, Nigeria does not have radioactive waste disposal facility (Salakhedinov and Agyeno, 2020). Nuclear waste and incident management is a critical hotspot in pursuit of NPP in Nigeria (Kim et al, 2021). Even though Nigeria has created a nuclear disaster emergency response plan, disaster and risk management is very poor and at best, nascent, in Nigeria. For example, Nigeria's emergency services were incapable of immediately locating the site of an airplane crash in Lagos, neither did they have the equipment to conduct a suitable rescue mission (Ejiogu, 2013). Geological disposal method is the usual form of disposing nuclear waste, but its sustainability has generated considerable debates (Aliyu et al, 2013). Radioactive waste has long decay period, and has long term implications on the disposal facilities (Kim et al, 2021).

**Nuclear materials**

NPP needs nuclear materials, especially uranium to run. A feasibility survey of uranium ore deposits was conducted in Bauchi State in 1976-1977 by the Federal Government of Nigeria. This led to the creation of Nigerian Uranium Mining Company (NUMCO), tasked with exploration, exploitation, processing and marketing. Globally, Niger, Nigeria's neighboring country holds around 10% of the commercially available uranium ore deposits. In the granitic zones of Nigeria, radioactive materials (uranium and thorium) exists in pyrochlore. In Kigom Hills, Plateau State, chemical analysis of the pyrochlore shows it contains 3.3% uranium, 3.3% thorium oxide and 41.1% niobium and tantalum oxides. Other areas with uranium potential are the phosphate in Abeokuta, Ososhun, Shoyinka and Ifo. Others are Sokoto, Niger, Benue and Cross Rivers State (Onyejekwe, 1981). Figure 5 shows states with identified uranium ores (adapted from Karnilyus and Ekedegwa, 2018).

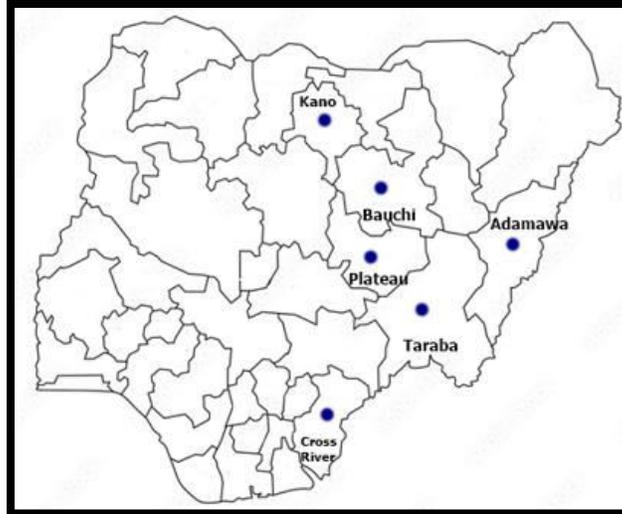


Figure 5: States with Recorded Uranium in Nigeria

As shown in figure 5, the states lie within northern regions of Nigerian, except for Cross Rivers. Based on promising geological environments for uranium deposits, few uranium explorations conducted in Nigeria indicated the country has substantial potential for uranium. In Mika, Gumchi, Zona and Mayo Lope locations in Adamawa State, core analysis shows a value of 2000 ppm U. Uranium reserve at Mika is estimated at 52 tU at a grade of 0.63% U and a vertical extent of 130 m, while the reserve of Gumchi is estimated at 100 tU at a grade of 0.90% U and a vertical extent of 200 m. The average or recommended value is usually 0.03% U (Karnilyus and Ekedegwa, 2018). The uranium reserve in Nigeria based on the limited exploration is estimated at 200 t U (Ewim et al, 2021). Conversely, Niger and Namibia have recoverable 276,400 and 448,300 metric tons of U, respectively as at 2019 (Statista, 2023). Therefore, even if Nigeria's uranium ore is not commercial, the neighboring countries of Niger, Gabon and Central Africa Republic which Nigeria has advantageous influence are major source of global uranium trade (Okolo, 1985). Other critical materials such as zirconium, molybdenum, graphite, tungsten, tantalum, chromium, lead and others required for construction of nuclear reactors (and NPP) exists in ores across Nigeria (Onyejekwe, 1981)

### Conclusion

This paper adopted systematic review to search, used set criteria to identify and select relevant studies on nuclear energy in Nigeria. This is important considering the growing emphasis on the role of nuclear energy to decarbonize or reduce GHG emissions in the power sector, so as to achieve climate objectives. The creation of NAEC in 1976 marks the initial initiation of the country's nuclear energy program. Our result shows that research on nuclear energy has been few and inconsistent over the years. Greater portion of the included studies (47%) dealt with energy or

low-carbon potential of NPP, to reduce or mitigate emissions in the energy sector. 35.3% dealt with environment and safety issues of NPP, including atmospheric dispersion (normal operation and accidental release) and seismicity; while 17.7% focuses on resources including human resources development, technical, political, financial and others. Identified themes or issues in the included studies consist of provision of (i) low-carbon or sustainable energy; (ii) human resources or manpower development to construct, operate and regulate NPP; (iii) safety and security concerns such as atmospheric dispersion (normal operation and or accidental release), human risk (poor maintenance culture, proliferation of nuclear materials, terrorism and militancy, corruption, etc), seismological risk and challenges posed by radioactive waste; and (iv) availability of nuclear materials such as uranium.

### **Recommendation**

- The federal government of Nigeria should expand the national grid capacity, which presently falls below IAEA technical recommendation (5-10%) for proposed NPP capacity.
- To develop local human resource capacity, the existing nuclear research centers such as Center for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, which host NIRR-1, should be licensed and accredited to run a specialized postgraduate programme on the different aspects of nuclear energy, in accordance with globally acceptable standards.
- Further, exchange academic and research programs between the proposed centers and those in advanced nuclear countries such as South Africa and global North should be developed to strengthen local capacity and enable knowledge transfer.

### **References**

1. *Abam F.I., Nwankwojike, B.N., Ohunakin, O.S. and Ojomu, S.A. (2014). Energy resource structure and on-going sustainable development policy in Nigeria: A review. International Journal of Energy and Environmental Engineering 5(102), 1-16.*
2. *Adepelumi, A.A. (2009). Short-term probabilistic forecasting of earthquakes occurrence in South-Western Nigeria. Technical Report Submitted to the Centre for Geodesy and Geodynamics, Toro, Nigeria.*
3. *Adewuyi, O.B., Kiptoo, M.K., Afolayan, A.F., Amara, T., Alawode, O.I. and Senjyu, T. (2020). Challenges and prospects of Nigeria's sustainable energy transition with lessons from other countries' experiences. Energy Reports 6, 993-1009.*

4. Afegbua, K.U., Ezmo, F.O., Osahon, O.D., Yakubu, T.A. and Sanni, H.T. (2019). *Probabilistic seismic hazard assessment for national planning and development in Nigeria. Journal of Geodynamics* 126, 46-55.
5. Ahmed, Y.A., Balogun, G.I., Jonah, S.A. and Funtua, I.I (2008). *The behaviour of reactor power and flux resulting from changes in core-coolant temperature for a miniature neutron source reactor. Annal of Nuclear Energy*, 35, 2417–2419.
6. Aliyu, A.S., Ramli, M.A. and Saleh, M.A. (2015). *Assessment of potential human health and environmental impacts of a nuclear power plant (NPP) based on atmospheric dispersion modeling. Atmosfera* 28(1), 13-26.
7. Aliyu, S.A., Ramli, A.T. and Saleh, M.A. (2014). *Environmental impact assessment of a new nuclear power plant (NPP) based on atmospheric dispersion modeling. Stochastic Environmental Research and Risk Assessment*, 1-15.
8. Aliyu, A.S., Ramli, A.T. and Saleh, M.A. (2013). *Nigeria electricity crisis: Power generation capacity expansion and environmental ramifications. Energy* 61, 354-367
9. Dehner, G., McBeth, M.K., Moss, R. and Woerden, I. (2023). *A zero carbon energy future? Lessons learned from perceptions of climate change and nuclear waste. Energies* 16(4), 1-16
10. Egieya, J.M., Ayo-Imoru, R.M., Ewim, D.R.E. and Agedah, E.C. (2022). *Human resource development and needs for nuclear power plant deployment in Nigeria. Nuclear Engineering and Technology* 54, 749-763
11. Ejiogu, A.R. (2013). *A nuclear Nigeria: How feasible is it? Energy Strategy Reviews*, 1, 261-265,
12. Eluyemi, A.A., Sharma, S., Olotu, S.J. et al (2020a). *A GIS-based site investigation for nuclear power plants (NPPs) in Nigeria. Scientific African* 7, 1-15.
13. Eluyemi, A.A., Ibitoye, F.I. and Baruah, S. (2020b). *Preliminary analysis of probabilistic seismic hazard assessment for nuclear power plant site in Nigeria. Scientific African* 8, 1-12.
14. *Federal Republic of Nigeria Official Gazette*, (2021). *Nigerian Safety Regulations for Licensing of Sites for Nuclear Power Plants, 2021. 108(28), B1057–B1107.*
15. *Grantham Research Institute on Climate Change and Environment. What is the role of nuclear in the energy mix and in reducing greenhouse gas emissions? The London School of Economics and Political Science, 2 December 2022. (www.lse.ac.uk)*
16. *IAEA, International Atomic Energy Agency (2021). Nuclear power 10 years after Fukushima: The long road back. (www.iaea.org)*
17. Ibrahim, H.F. and Ayomoh, M.K. (2022). *Optimum predictive modeling for a sustainable power supply mix: A case of the Nigerian power system. Energy Strategy Reviews* 44, 1-14.

18. Ishola, F.A., Olatunji, O.O., Ayo, O.O. et al (2019). Sustainable nuclear energy exploration in Nigeria – A SWOT analysis. *Procedia Manufacturing* 35, 1165-1171.
19. Jackson, I. (2009). Nuclear energy and proliferation risks: Myths and realities in the Persian Gulf. *International Affairs*, 85, 1157-1172.
20. Jewell, J. (2011). Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs. *Energy Policy* 39, 1041-1055.
21. Jonah, S.A., Liaw, J.R., Matos, J.E. and Monte Carlo (2007). Simulation of core physics parameters of the Nigeria Research Reactor-1 (NIRR-1). *Annal of Nuclear Energy*, 34, 953–957.
22. Jonah, S.A., Ibikunle, K. and Li. Y. (2009). A feasibility study of LEU enrichment uranium fuels for MNSR conversion. *Annal of Nuclear Energy*, 36, 1285–1286.
23. Karnilyus, J.S. and Ekedegwa, A.I.G. (2018). Uranium potential in Nigeria. *Nigeria Atomic Energy Commission*, 193-195. ([www.iaea.org](http://www.iaea.org))
24. Kaya, Y., Yamaguchi, M. and Geden, O. (2019). Towards net zero CO<sub>2</sub> emissions without relying on massive carbon dioxide removal. *Sustainability Science* 14, 1739-1743.
25. Lee, S., Kim, M. and Lee, J. (2017). Analyzing the impact of nuclear power on CO<sub>2</sub> emissions. *Sustainability*, 9, 1428.
26. Liverpool-Tasie, S.O., Sanou, A. and Tambo, J.A. (2019). Climate change adaptation among poultry farmers: Evidence from Nigeria. *Climate Chang* 157, 527-544
27. *Nigeria Energy Transition Plan: Nigeria’s pathway to achieve carbon neutrality by 2060.* ([www.energytransition.gov.ng](http://www.energytransition.gov.ng))
28. Nwozor, A., Oshewolo, S, Owwoye, G. and Okidu, O. (2021). Nigeria’s quest for alternative clean energy development: A cobweb of opportunities, pitfalls and multiple dilemmas. *Energy Policy*, 149, 1-12.
29. Okafor, C., Madu, C., Ajaero, C., Ibekwe, J., Bebenimibo, H. and Nzekwe, C. (2021). Moving beyond fossil fuel in an oil-exporting and emerging economy: Paradigm shift. *AIMS Energy* 9(2), 379-413.
30. Okafor, C.C., Nzekwe C.A., Ajaero, C.C., et al. (2022). Biomass utilization for energy production in Nigeria: A review. *Cleaner Energy Systems* 3, 1-17.
31. Ajaero, C.C., Okafor, C.C., Festus, F.A. et al (2023). Energy production potential of organic fraction of municipal solid waste (OFMSW) and its implications for Nigeria. *Clean Technologies and Recycling*, 3(1), 44-65.
32. Okon, E.M., Falana, B.M., Solaja, S.O., et al. (2021). Systematic review of climate change impact research in Nigeria: implication for sustainable development. *Heliyon* 7, 1-21.

33. Onyejekwe, D.C. (1981). *Prospects for the development of nuclear technology in Nigeria. Energy* 6(10), 1053-1057.
34. Prävǎlie, R. and Bandoc, G. (2018) *Nuclear energy: between global electricity demand, worldwide decarbonisation imperativeness, and planetary environmental implications. Journal of Environmental Management*, 209, 81–92.
35. Price, J., Keppo, I. and Dodds, P.E. (2023). *The role of new nuclear power in the UK's net-zero emissions energy system. Energy* 262, 1-12.
36. Sah, A., Lovering, J, Maseli, O, and Saxena, A. (2018). *Atoms for Africa: Is There a Future for Civil Nuclear Energy in Sub-Saharan Africa? CGD Policy Paper. Washington, DC: Center for Global Development. (www.cgdev.org)*
37. Solaun, K. and Cerda, E. (2019). *Climate change impacts on renewable energy generation. A review of quantitative projections. Renewable and Sustainable Energy Reviews* 116, 1-16.
38. Statista, 2023. *Uranium resources in Africa as of 2019 by country. (www.statista.com)*
39. van der Wiel, K., Stoop, L.P., van Zuijlen, B.R.H., Blackport, R et al (2019). *Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall. Renewable and Sustainable Energy Reviews* 111, 261-275.
40. Vujic J., Antic DP, Vukmirovic Z (2012). *Environmental impact and cost analysis of coal versus nuclear power: The U.S. case. Energy*, 45, 31-42.
41. Yarwood, D.R. and Doser, D.I. (1989). *Deflection of oceanic transform motion at a continental margin as deduced from waveform inversion of the 1939 Accra, Ghana earthquake, Tectonophysics* 172, 341–349.
42. Zhan, L, Bo, Y, Lin, T. and Fan, Z. (2021). *Development and outlook of advanced nuclear energy technology, Energy Strategy Reviews*, 34, 1-4.