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Review of the Nuclear Industry in Africa, Focusing on Nigeria and in Comparison With South Africa

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Abstract
Economic development and improving the quality of life are made easier with access to reliable and affordable electricity. Africa, alas, is faced with severe challenges in satisfying the energy needs of its over 1.4 billion people. Despite the continent's endowment with surplus energy resources like oil, coal, uranium, and gas, the power supply is far superseded by its demand. The continent's industrial sector has been impinged by this energy deficit, with about 700,000 gigawatt-hours (GWh) of electricity needed to maintain its activities as of November 2019. To attain sustainable development, Africa must develop eco-friendly energy systems to address this energy crisis, and nuclear power inclusion in Africa's energy mix is a proposed alternative. Ghana, for instance, initially proposed 2029 as its target year to add nuclear power to its energy generation mix. This research project examines the history and current status of Africa's nuclear sector, focusing on Nigeria while making comparisons with South Africa. The study uses the SWOT analysis principle to evaluate the internal strengths, weaknesses, external opportunities, and inherent threats connected to Nigeria's nuclear power agenda. The research discovered that although Nigeria fulfils the basic requirements for including nuclear power in its energy mix, building a nuclear energy facility could be marred by significant gaps. Public perception and policy changes due to political transitions constitute the major setbacks to the timely execution and operation of Nigeria's nuclear power facility. Financing is a critical impediment that needs to be addressed, and the research suggests a plethora of funding alternatives to expedite Nigeria's development of a nuclear facility. Also, the South African nuclear industry's status was reviewed. Overall, the study concludes that Nigeria possesses several strengths and opportunities for nuclear power generation that are economically feasible. On the contrary, to ensure energy security in South Africa, its nuclear power generation needs to be expanded for a diversified energy mix that fosters economic development.

Keywords: *Africa, Nigeria, South Africa, Nuclear power, SWOT analysis, Financing*

1. Introduction

The development of nations globally is hugely dependent on the critical role of energy. A nexus between poverty and access to reliable, affordable power is shown by research [1]. The industrial sector drives economic growth, and this demands a primary input in the form of energy. Unfortunately, Africa's power demand largely surpasses supply despite the continent's endowment with abundant energy resources such as oil, gas, coal, cobalt, platinum, and uranium – a plight that impedes the continent's development. With over 1.4 billion inhabitants [2,3], Africa is the world's second-largest and most populous continent [3]. However, with an epileptic power supply being characteristic of the connected fragment [3], access to electricity exists in only 43 % of her population. This energy crisis has crippled Africa's industrial sector, as about 700 000 gigawatt-hours (GWh) of electricity was required to maintain its activities as of November 2019 [3,4]. While the Energy Commission of Nigeria (ECN) reports the annual expenditure of its members to be above $4.3 billion on private power generators due to a deficit in energy supply [3,5,6], 40 % of Nigeria’s production cost is attributable to energy, which is nine times that of China, negatively impacting the lucrativeness of the nation’s industries [3,5]. Nigeria’s growing population and her quest for industrialization and urbanization have been catalysts to her energy crisis. However, progress has been made in developing its nuclear power industry. A Memorandum of Understanding (MoU) was signed in 2010 between the Nigeria Atomic Energy Commission (NAEC) and the State Atomic Energy Corporation of the Federation of Russia (ROSATOM) to construct a nuclear power plant in Nigeria [5,7]. Within this agreement, Nigeria ‘was to purchase’ a Russian model VVER (water-water energetic reactor) with 1200 MW capacity. However, this agreement is yet to be realized at the time of this research. In 2017, NAEC and the International Atomic Energy Agency (IAEA) signed a memorandum of understanding to further develop the country's nuclear capabilities [7,8].

Africa has a long history of nuclear technology, with the mid-20th century witnessing several countries establishing nuclear research and development programs [7]. However, Africa’s nuclear industry has experienced insignificant growth, as only South Africa actively utilizes a nuclear power source [2]. In contrast, nuclear research and development has gained the interest of other African nations – such as Nigeria. The establishment of NAEC by the Nigerian government in the 1960s [7] to oversee the development of nuclear technology was the precursor to Nigeria’s nuclear program. In subsequent decades, Nigeria trained several national scientists and engineers in nuclear technology as an investment in human resources for nuclear research and development, of which the author is a beneficiary of such investment. Despite these efforts, Nigeria is still laid back in generating power through nuclear energy sources. As the nation is yet to construct its commercial nuclear power plant, it has resultantly relied heavily on fossil fuels for power generation. However, a continuous focus on research and development by Nigeria's nuclear program, especially on the use of nuclear technology for medical purposes [7], has remained persistent.

Fusion, fission, or nuclear decay reactions can generate nuclear energy [9]. Often seen as a substitute for energy generated from hydrocarbons or fossil fuels, nuclear energy is not a perfect alternative to transportation. However, it is highly effective in electricity generation. Fossil fuel power plants are replaceable with nuclear power in developed and developing countries globally. It is envisioned that shifting from traditional energy sources to nuclear energy would reduce crude oil demand and greenhouse gas emissions. Nigeria and many other African nations have established the African Network for Enhancing Nuclear Power Program Development to promote the development of nuclear energy in the continent [2,10].

This study employed a SWOT analysis to examine the strengths, weaknesses, opportunities, and threats of nuclear power development in Nigeria. The analysis data was gathered from existing literature and documents on global nuclear energy projects. This study is imperative due to potential challenges that may need to be resolved or mitigated during the implementation, development, and operation of a nuclear facility in Nigeria. Safety and cost are the most relevant considerations for a nuclear power plant’s adoption. The study is organized as follows: Chapter 1 discusses Nigeria's nuclear industry's history and present status, the public’s perceptions of the industry, and the country's energy sector composition. Chapter 2 explains the methodology used for the analysis. The results and discussions of the SWOT analysis and financing options for developing Nigeria’s nuclear power sector are presented in Chapter 3, including energy policy and the energy sector’s organizational setup.

Chapter 4 compared the South African nuclear industry with Nigeria's by reviewing its status. The conclusion and recommendation are highlighted in Chapter 5.

1.1. Description of Nigeria's geographical location

Nigeria is located in West Africa. It is bordered by Benin to the west, Niger to the north, Chad to the northeast, Cameroon to the east, and to the South, the Gulf of Guinea (Atlantic Ocean). The latitudes of Nigeria lie between 4°N and 14°N, and the longitudes range from 2°E to 15°E [2]. While Nigeria is the eighth-most populous country globally, it is Africa's most populous country. It has an overall land area of about 923,768 square kilometers. Abuja is Nigeria's capital city, located in the country's center at approximately 9°N latitude and 7°E longitude [3,11]. Nigeria's official and working language is English, and its population is diverse, with hundreds of ethnic groups.

Nigeria is home to several rivers and lakes. Some of the major rivers in Nigeria include the Niger River, the longest river in West Africa and the third longest on the continent, and the Benue River, the longest tributary of the Niger River. Other vital rivers in Nigeria include the Cross River, the Imo River, the Osun River, the Ogun River, and the Sokoto River. Nigeria boasts a variety of lakes, with Lake Chad, one of Africa's largest lakes, residing in its northern region. Additionally, the country is home to Lake Kainji, an artificial lake formed by the Kainji Dam on the Niger River. In the southwestern part of Nigeria, you'll find Lake Oluwa [8,11]. Moreover, Nigeria features smaller lakes, including Lake Alau, Lake Egbin, and Lake Turkana. These bodies of water serve a crucial purpose in the context of a potential nuclear facility with the possibility of providing the necessary coolants. This makes Nigeria a promising location for establishing a Nuclear Power Plant (NPP).

1.2. Nigeria's energy demand and current composition of the power sector

Nigeria, with a population exceeding 211.4 million, stands as Africa's largest economy and is witnessing a substantial surge in electricity demand [2,3]. The Nigerian Electricity Regulatory Commission (NERC) reported that as of December 2019, the nation had an installed electricity generation capacity of 12,522 megawatts (MW) [3,4,12]. However, the actual electricity production is often limited, typically hovering around 4,000 MW on most days. This capacity falls short of meeting the needs of a country with such a significant population [2,3,5,12]. Remarkably, roughly 60 % of the population has electricity access, with 86 % of urban and 34 % of rural residents connected to the grid [12]. Nigeria's electricity generation lags behind its potential due to various challenges, including outdated and insufficient transmission and distribution infrastructure. Nigeria's predominant electricity sources are thermal, primarily biofuels and waste, followed by oil and natural gas [12]. Nigeria's electricity generation mix includes hydroelectric power and coal alongside other sources. As of December 2019, as depicted in Figure 1, the majority of electricity generation, a significant 74.74 %, is attributed to biofuels and waste power plants. Following closely is oil, contributing 15.13 % to the total generation. Natural gas, hydroelectric, and coal collectively make up 9.74 %, 0.37 %, and 0.02 % of the entire electricity generation, excluding off-grid sources [2,5,12].

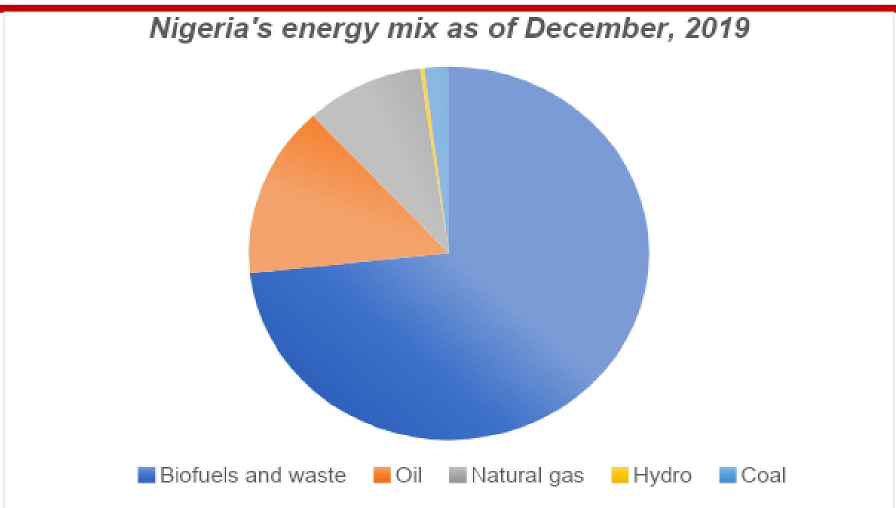

Figure 1: Nigeria's electricity generation mix as of December 2019 [2], *excluding off-grid generation*

The Nigerian government has initiated various measures to enhance its electricity generation capacity and ensure a dependable power supply. These initiatives encompass the establishment of new power plants, the expansion of existing ones, and the rehabilitation and modernization of transmission and distribution infrastructure. Furthermore, Nigeria has introduced several solar and wind power projects, mainly serving off-grid electrification in remote regions. The government aims to augment the share of renewable energy in the country's energy portfolio, seeking to diminish its dependence on fossil fuels [3,5,13]. However, the progress in this direction has been somewhat sluggish due to a scarcity of investment and regulatory hurdles. Similarly, including nuclear power in Nigeria's energy generation mix remains possible but requires swifter action [2,11,14].

Figures 2, 3, 4, 5, and 6 represent data across several categories of Nigeria's energy system and macroeconomic metrics. These categories include [3]:

- Key aspects of Nigeria's energy system.
- Important macroeconomic indicators like GDP, carbon dioxide (CO_2) emissions, and metrics related to electricity access and clean cooking access in two scenarios: Stated Policies and Africa Case.
- Explanations of energy-related policy initiatives, along with specific performance goals.
- Projections detailing the development of primary energy demand and GDP (using 2018 dollars in purchasing power parity terms) until 2040, focusing on the roles of different fuels in shaping alternative energy scenarios.
- Insights into how the electricity supply composition evolves to meet increasing demands.
- Energy consumption data in various scenarios, illustrating the potential efficiency improvements achieved through stricter fuel economy standards, building codes, and efficiency requirements for equipment and appliances.
- A comparison of the fuel types and cooking methods used in 2018 versus those projected for 2030 under two scenarios.
- Pathways related to the demand and production of significant fossil fuels, specifically focusing on trade balances.
- The overall financial commitment required in various sectors to meet the growing energy demand and supply in two scenarios.

The two scenarios under consideration are the Stated Policies and the Africa Case. The Stated Policies scenario outlines Nigeria's anticipated "performance and industrial development objectives," focusing on a diversified energy mix. These performance targets encompass:

- Achieving a 20 % reduction in greenhouse gas emissions by 2030, with an optional 45 % reduction.
- Increasing daily oil production to 2.5 million barrels and becoming a net exporter.
- Phasing out gas flaring by 2030.

The industrial development targets are centered on the following objectives:

- Allocating at least 30 % of the national budget to infrastructure and long-term investments.
- Attaining a 7 % GDP growth and creating over 15 million job opportunities by 2020, doubling the manufacturing sector's contribution to 20 % of GDP by 2025.

Nigeria maintains its status as Africa's largest economy. In the Africa Case scenario, the following observations emerge:

- To fulfill the energy requirements of an economy tripling the size of that in 2018, a more diversified energy source approach would result in decreased energy demand.
- The utilization of gas to address the growing energy demand is on an upward trajectory, attributable to the government's gas master plan.

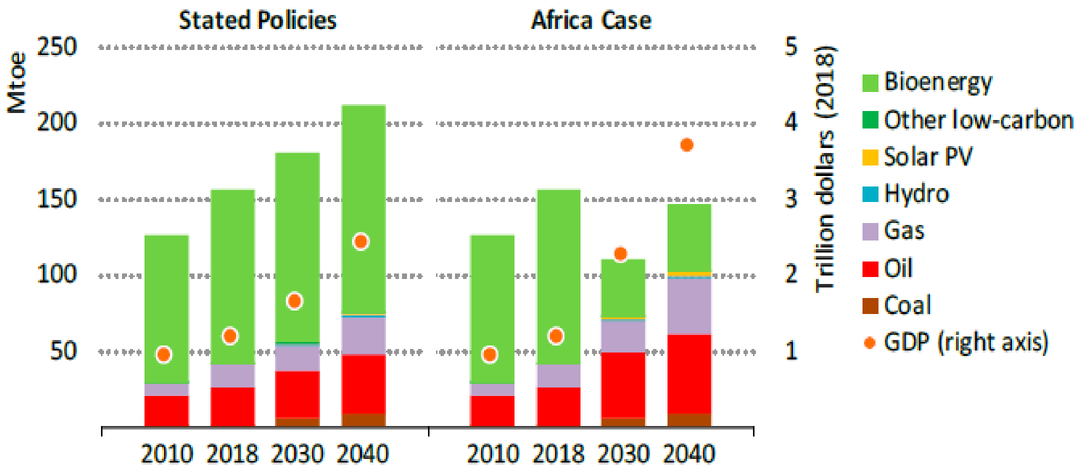

Figure 2 [3]*: Nigeria's primary energy demand under the Stated Policies scenario and the Africa Case, alongside Gross Domestic Product (GDP)*

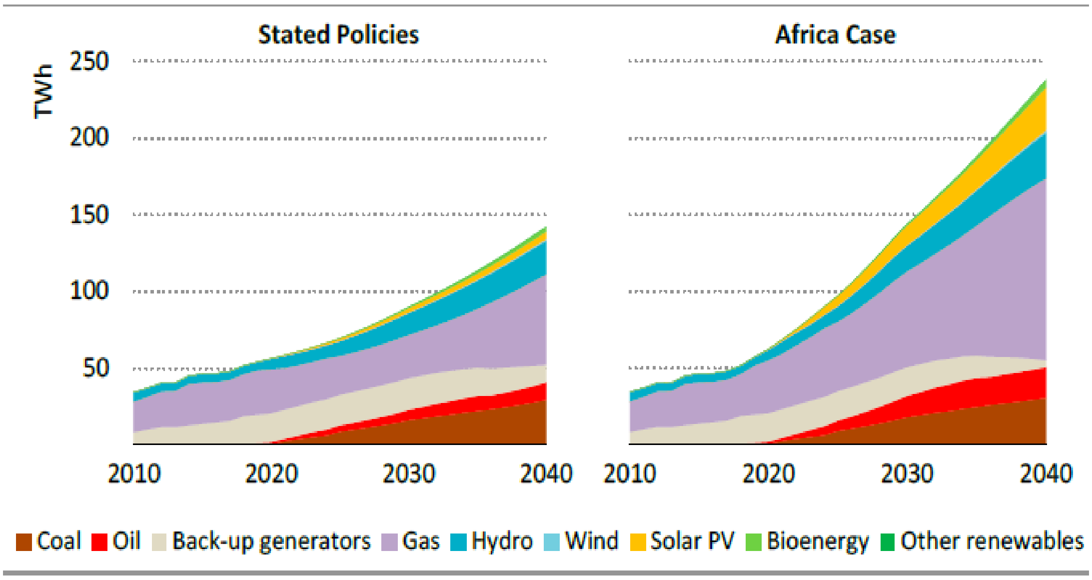

Figure 3 [3]*: Nigeria's electricity generation by technology (Stated Policies) with a projection to 2040. As can be seen, In Africa, natural gas is the primary source of electricity. However, there is a trend towards using solar PV as a power source as the continent taps into its sizeable solar energy potential.*

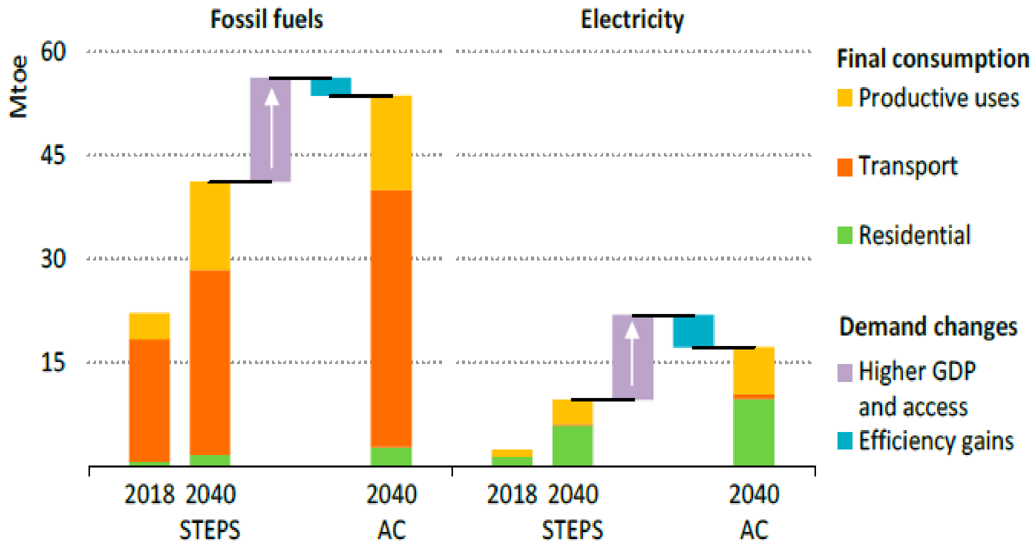

Figure 4 [3]*: Nigeria's final energy consumption (STEPS – Stated Policies Scenario), including the Africa case (AC) with a projection to 2040.*

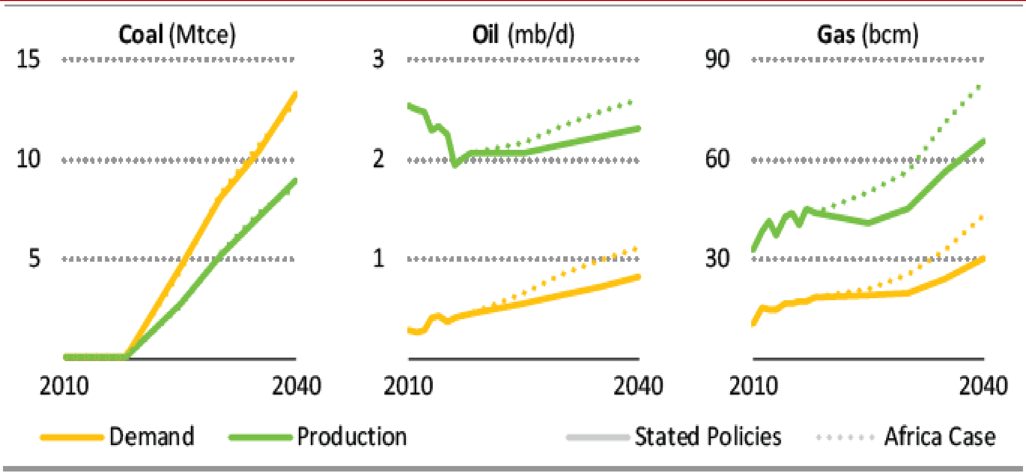

Figure 5 [3]*: Nigeria's fossil fuel demand and production projected to 2040. Both scenarios show that demand for fossil fuels, specifically gas, is increasing in the industry and power sectors. In response to this increase in demand, efforts are being made to increase production and reduce gas flaring.*

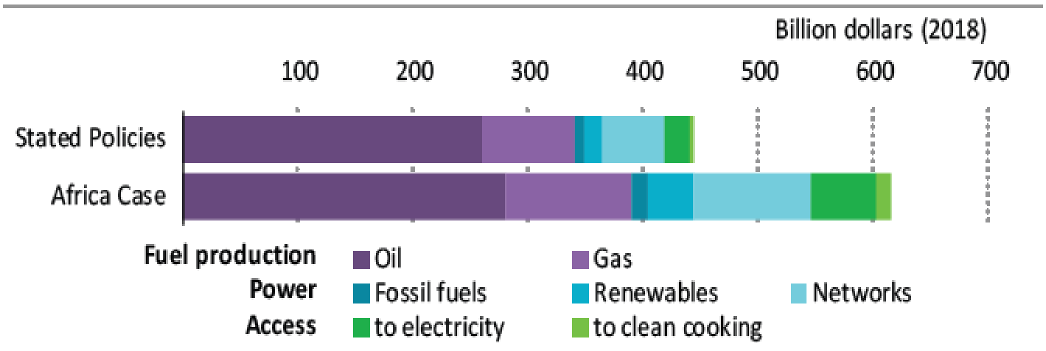

Figure 6 [3]*: Nigeria's cumulative investment needs, 2019 – 2040. As seen in the Stated Policies Scenario, a total investment of $445 billion in energy supply is required, with approximately 80 % allocated towards the upstream oil and gas sector.*

1.3. Comparing the energy cost of nuclear power with other forms of energy

The energy cost associated with nuclear power varies based on factors like the type of reactor, fuel availability, and the expenses involved in constructing and operating the plant. However, as a general trend, nuclear power tends to be a cost-effective option for generating electricity compared to other energy sources. According to the US Energy Information Administration (EIA), the levelized cost of electricity (LCOE) from new nuclear power plants is often competitive with other methods of electricity generation, including coal, natural gas, and renewable sources like wind and solar. The LCOE represents the average expense of electricity generation over a power plant's lifespan, factoring in initial capital outlays, fuel expenses, and operating and maintenance costs [15].

The LCOE for nuclear power is subject to several influencing factors, including financing availability, fuel costs, and the expenses of decommissioning the plant at the end of its operational life. Nevertheless, nuclear power often proves to be a financially viable means of generating electricity, especially when considering the external factors, such as the environmental and health consequences of burning fossil fuels. In essence, the cost of nuclear power can also be shaped by policy and regulatory elements, including subsidies and incentives for renewable energy sources, making these alternatives more competitive in contrast to nuclear power. Moreover, the cost of nuclear power may exhibit regional disparities due to substantial initial capital outlays and the necessity for specialized infrastructure and a skilled workforce in some locations [15].

The introduction of the Russian VVER reactor, a 1200 MW model, is anticipated to impact Nigeria's energy generation cost significantly. Incorporating nuclear energy into the energy mix is expected to bolster the country's installed capacity and concurrently diminish greenhouse gas emissions. However, there is a notable apprehension regarding the safety perception associated with Soviet reactor designs, particularly when compared to Western counterparts, in the context of employing the Russian-model VVER reactor in Nigeria.

Soviet nuclear reactors, serving both civilian and military purposes, have been a subject of scrutiny and concern due to a series of high-profile accidents and incidents. Key incidents include:

- Chernobyl Disaster (1986): The Chernobyl nuclear power plant accident was the most infamous instance of a Soviet reactor design failure. The explosion and ensuing fires at Reactor No. 4 resulted in a significant release of radiation into the environment, marking one of the worst nuclear disasters in history. Design flaws, inadequate safety measures, and a culture of secrecy and lack of transparency in the Soviet Union played significant roles in the catastrophe.
- Kyshtym Disaster (1957): The Kyshtym disaster at the Mayak Production Association, a Soviet nuclear facility, entailed the explosion of a radioactive waste storage tank, releasing a substantial amount of radioactive material into the environment. Once again, secrecy and an absence of information-sharing contributed to the scale of the disaster.
- RBMK Reactor Design: The Chernobyl reactor, an RBMK-1000 model, featured inherent safety flaws, including a positive void coefficient, meaning that as coolant (water) vaporized, reactor power increased rather than decreased. This design characteristic made the reactor more susceptible to accidents if not cautiously operated.
- Secrecy and Lack of Transparency: The Soviet Union maintained a culture of secrecy and reluctance to disclose information regarding nuclear incidents and accidents, making it challenging to assess the safety of their reactor designs. This lack of transparency hindered international collaboration and safety enhancements.
- Military Applications: The Soviet Union also employed nuclear reactors for military purposes, including in submarines and icebreakers. These reactors were often shrouded in secrecy, and their safety records are not as extensively documented as civilian reactors.

It's crucial to recognize that not all Soviet reactor designs were inherently unsafe. Many of these reactors operated safely for extended periods, with some even considered technologically advanced at the time. However, the perception of safety in Soviet reactor designs has been significantly shaped by the well-publicized disasters and the secretive nature of the Soviet nuclear program. Following the Chernobyl accident, there were endeavors to enhance safety standards in the former Soviet Union, aided by international organizations focused on upgrading reactors and improving safety protocols. Nonetheless, the historical impact of past accidents continues to influence how Soviet reactor safety is viewed today.

Finally, in my opinion, considering recent geopolitical events involving Russia and Ukraine, I would strongly recommend that the Nigerian government reevaluate its decision to adopt the Russian-model VVER reactor. Russia may face substantial economic sanctions from Western nations soon, which would have repercussions for any country engaging in bilateral relations with Russia. Thus, considering potential economic and diplomatic consequences, it is a valid recommendation for the Nigerian government to reconsider its choice of a Russian-model nuclear reactor for power generation.

Nuclear technology stands out for its ability to generate power efficiently using a relatively small amount of uranium, setting it apart from conventional energy sources. The United States Energy Information Administration has furnished data concerning the (LCOE) for various energy sources. According to Lazard's 2018 analysis in Table 1 [16], nuclear power plants often incur higher costs than hydrocarbons and renewable sources. However, this cost differential should be considered beyond mere profitability, particularly when evaluating the environmental consequences primarily associated with fossil fuels and their negative impact of CO_2 emissions.

Moreover, the considerable uncertainty surrounding energy policies and the perceived risks attached to specific technologies can lead to investors seeking higher compensation, rendering certain technologies less financially viable [15]. Although renewables like solar and wind energy may offer lower costs than nuclear power, as shown in Table 1, their reliability can be challenged by factors such as variability and atmospheric conditions, making them potentially less dependable than nuclear energy.

Type of technology	**LCOE ($/MWh)**
Alternative energy	
Solar PV – Rooftop Residential	160 – 267
Solar PV – Community	73 – 145
Solar thermal tower with storage	98 – 181
Fuel cell	103 – 152
Geothermal	71 – 111
Wind	29 – 56
Conventional energy	
Gas peaking	152 – 206
Nuclear	112 – 189
Coal	60 – 143
Gas combined cycle	41 – 74

Table 1 [16]*: Comparison of the levelized cost of energy without subsidies*

1.4. Nigerians' public perceptions of the NPP project and the associated radioactive waste

The topics of nuclear power and radioactive waste management spark controversy in many nations. Within the democratic context of Nigeria, it is expected that public opinions on these matters may exhibit a wide range of perspectives. Thus, it is essential to approach any nuclear power plant project with meticulous planning, emphasizing safety protocols and radioactive waste handling. Given the potential diversity of views within the populace and various communities, it would be ethically unsound to generalize the public's stance on a nuclear power plant project and the associated radioactive waste in Nigeria. Nevertheless, existing literature suggests the presence of an ongoing debate and discourse regarding the prospective advantages and drawbacks of nuclear power in Nigeria.

Some individuals advocate for establishing a nuclear power plant in Nigeria to enhance energy production and reduce the country's reliance on fossil fuels. Proponents of nuclear power argue that it represents a dependable and environmentally friendly energy source that could address Nigeria's energy needs while also contributing to the global fight against climate change. Conversely, others harbor concerns about nuclear power's safety and environmental consequences. These concerns encompass potential risks related to accidents and the complex challenge of managing radioactive waste over the long term. Additionally, some individuals express concerns about the financial costs of constructing and operating a nuclear power plant and the associated risks of technology proliferation [17,18]. It is crucial to ensure that the public is well-informed and actively engaged in the decision-making process to understand the potential benefits and drawbacks of a nuclear power plant project. The government should carefully consider all these factors before deciding on the project's viability.

Nuclear power plants (NPPs) have encountered resistance and concerns in Africa, resulting in the abandonment of projects or significant delays in their implementation despite their potential benefits. These concerns often stem from misconceptions, exaggerated fears, and international political factors. However, in other regions of the world, NPPs have generally maintained a relatively safe track record over the past 50 years of commercial operation, with a limited number of, though tragic, accidents occurring during this period. The Fukushima Daiichi incident in 2011 triggered a global review of nuclear energy policies, temporarily slowing down the progress of this technology. However, substantial safety measures have since been introduced and enhanced [19]. According to the Nuclear Energy Agency (NEA), these reassessments have largely diminished.

Nigerian citizens were the subjects of a survey aimed at gauging their views on the nuclear power program. Ewim et al. [17] conducted a study to explore Nigerians' attitudes toward nuclear energy as a potential electricity source in Nigeria. The research employed a quantitative approach, involving 10,001 participants surveyed using social networking platforms and hand-delivered questionnaires. Notably, the response rate reached 71%. The data underwent analysis utilizing Pearson's Product Moment Correlation and IBM SPSS software to ascertain the correlation between various viewpoints on nuclear power and its potential to address Nigeria's electricity challenges. The study's Cronbach's alpha value, standing at 0.821, affirmed its reliability and validity within the defined scope. The results revealed that more than 56 % of the respondents supported nuclear power as a feasible electricity option in Nigeria. Furthermore, the study highlighted the potential positive impacts of nuclear power on the Nigerian economy, safety, security, and environmental sustainability. Ewim et al. concluded that there were favorable perceptions regarding constructing a nuclear power plant in Nigeria [17].

Table 2 [17] provides a breakdown of the respondents' demographics, numerical findings, and an analysis of the survey data of each variable under examination. The survey results were assessed in terms of agreement percentages and the strength of correlations. Concerning the disposal of radioactive waste, findings from various studies consistently highlight that the management of radioactive waste is a noteworthy apprehension for those contemplating utilizing nuclear power as an energy source in Nigeria. The survey data revealed that a substantial majority (63.36 %) of respondents either strongly agreed or agreed that radioactive waste disposal is a significant obstacle to adopting nuclear power. Furthermore, an interesting yet statistically significant negative correlation ($r = -0.101$, $p = 0.002$) was observed between the perception of nuclear power as a viable option and concerns surrounding the disposal of radioactive waste [17]. Consequently, selecting a remote location for a nuclear power plant in Nigeria becomes crucial for minimizing the associated risks and hazards linked to radioactive waste. Establishing robust oversight and policies for radioactive waste disposal to ensure public safety and prevent potential accidents is equally vital.

Demographics	Description	Percentage (%)
Age	18 years – 30 years	35
	31 years – 50 years	45
	51 years and above	20
Location	Urban	60
	Rural	40

Table 2 [17]*: The demographics of respondents and results (%) of the Opinion Poll on implementing a nuclear power plant in Nigeria.*

In a separate research endeavor conducted by Sambo and Rafiu [18], it was observed that most participants in Nigeria held a positive outlook regarding nuclear power. This study amalgamated both primary and secondary data sources. Initial data gathering involved the administration of questionnaires utilizing random sampling, while secondary data was drawn from various references, including literature from prior studies conducted globally on related subjects. The questionnaire data underwent statistical analysis, utilizing the Kruskal-Wallis test and an independent sample T-test. The Kruskal-Wallis results indicated that different age groups exhibited statistically significant differences in their perspectives on nuclear power. Nevertheless, the independent sample T-test demonstrated that both genders showed similar support or opposition to nuclear energy in the country. Overall, the study unearthed substantial support for nuclear power in Nigeria and proposed that nuclear facilities could be judiciously located in remote areas to enhance the nation's energy security [18].

Demographic characteristics		Frequency	Percentage (%)
Gender	Male	821	68.8
	Female	373	31.2
Age of respondents	18 – 27	117	9.8
	28 – 37	209	17.5
	38 – 47	348	29.1
	48 – 57	289	24.2
	58 and above	231	19.4
Level of education	Masters/PhD	273	22.9
	Bachelor/HND	241	20.2
	Diploma/NCE/Grade 2	188	15.7
	SSCE	246	20.6
	FSLC	246	20.6
Employment status	Full-time working	208	17.4
	Part-time working	120	10.1
	Unemployed	149	12.5
	Retired	310	26.0
	Student	407	34.0

Table 3 [18]*: Demographic characteristics of respondents. A total of 1194 respondents completed the survey.*

Perception	Frequency	Percentage (%)

Very negative	32	2.7
Negative	90	7.5
Undecided	187	15.7
Positive	418	35.0
Very positive	467	39.1
Total	*1194*	*100*

Table 4 [18]*: Respondents' perception of nuclear power in Nigeria with a very high frequency of positive response.*

	Frequency	**Percentage (%)**
Strongly oppose	40	3.4
Oppose	100	8.4
Undecided	126	10.5
Support	399	33.4
Strongly support	529	44.3
Total	*1194*	*100*

Table 5 [18]*: Respondents' support or opposition to building a nuclear power facility in Nigeria. As the table shows, 44.3 % of the respondents strongly support building a nuclear power facility in Nigeria. This implies that many Nigerians anticipate the timely inclusion of nuclear energy in Nigeria's energy generation mix.*

Introducing nuclear power in any country requires meticulous planning, strict adherence to safety measures, and close collaboration with international bodies like the International Atomic Energy Agency (IAEA). As a nuclear technology specialist, I offer the following recommendations to mitigate potential risks and ensure the safe implementation of nuclear power in Nigeria:

- **Reforming the Regulatory Framework**: It is imperative to revamp Nigeria's existing nuclear regulatory authority (NNRA), which is responsible for licensing, monitoring, and enforcing safety standards, ensuring that regulations are contemporary and aligned with global best practices.
- **Strategic Site Selection**: The Nigerian government must carefully select appropriate locations for nuclear power plants, considering factors like geological stability, proximity to water sources for cooling, and distance from densely populated areas.
- **Modern Design and Technology Selection**: Opt for contemporary nuclear reactor designs with inherent safety features, such as pressurized water reactors (PWRs) or boiling water reactors (BWRs), known for their reliable safety records.
- **Cultivating a Strong Safety Culture**: Foster a robust safety culture within the nuclear industry, emphasizing safety at all levels of operation and management.
- **Effective Emergency Preparedness and Response**: Establish comprehensive emergency plans and response procedures in collaboration with local authorities, regularly conducting drills and exercises to ensure readiness for various scenarios.
- **Enhanced Security Measures**: Implement stringent security protocols to protect nuclear facilities against unauthorized access, theft, or acts of terrorism, encompassing both physical security and cybersecurity measures.
- **Efficient Waste Management**: Develop a comprehensive plan for the safe and secure storage, transportation, and disposal of nuclear waste generated by the power plants.
- **International Cooperation**: Collaborate with international organizations like the IAEA to leverage their expertise, guidance, and peer review processes and actively participate in international conventions and agreements related to nuclear safety.

- **Public Outreach and Education**: Promote public awareness and education about nuclear power, addressing misconceptions and concerns through transparent communication with the Nigerian population.
- **Training and Human Resources**: Ensure a well-trained workforce with the necessary nuclear technology, safety, and operations expertise. This workforce should also be responsible for designing a Nigerian-model nuclear reactor.
- **Robust Quality Control and Maintenance**: Implement rigorous quality control measures during construction and operation, and establish robust maintenance programs to ensure nuclear facilities' continuous safety and reliability.
- **Continuous Safety Assessment**: Conduct regular safety assessments and incorporate lessons learned from domestic and international incidents or accidents.
- **Financial Responsibility**: Allocate adequate financial resources for constructing, operating, and decommissioning nuclear facilities.
- **Sustained Political Commitment**: Secure long-term political commitment to nuclear safety and regulatory independence to maintain consistency in policies and practices.
- **Public Engagement**: Solicit input and feedback from the public, stakeholders, and experts throughout the planning, licensing, and operation of nuclear power plants

Recognizing that the successful introduction of nuclear power generation relies on a steadfast commitment to safety, thorough planning, and continuous vigilance is essential. Nigeria should approach this endeavor cautiously, prioritizing safety and drawing valuable lessons from established nuclear nations. Furthermore, they should consistently refine their methods and protocols in response to advancing technology and evolving global best practices.

1.5. Nigeria's nuclear energy development: Overview and roadmap

Several initiatives have been undertaken to explore the utilization of nuclear energy in Nigeria, with the inception of the Nigeria Atomic Energy Commission (NAEC) dating back to 1976 [7]. In 1978, the Federal Government of Nigeria took a significant step by establishing the first two university research and training centers, namely, the Centre for Energy Research and Development (CERD) at Obafemi Awolowo University in Ile-Ife and the Centre for Energy Research and Training (CERT) at Ahmadu Bello University in Zaria [7,17]. While the NAEC was initially formed in 1976, it became fully operational in 2006 [7,17]. In 1995, the Nigerian Nuclear Regulatory Authority (NNRA) was founded to oversee nuclear activities within the country, officially commencing its operations in 2001 [7,17]. Since 2006, there has been a significant expansion in the capacity and infrastructure of the national nuclear program, marked by the addition of four additional research centers. This has increased the number of nuclear research centers affiliated with the NAEC to seven. These centers include:

- Centre for Energy Research and Training (CERT) at Ahmadu Bello University in Zaria, Kaduna State
- Centre for Energy Research and Development (CERD) at Obafemi Awolowo University in Ile-Ife, Osun State
- Nuclear Technology Centre (NTC) at Sheda Science and Technology Complex in Abuja, FCT
- Centre for Nuclear Energy Studies (CNES) at the University of Port-Harcourt in Port-Harcourt
- Centre for Nuclear Energy Research and Training (CNERT), University of Maiduguri, Maiduguri
- Centre for Nuclear Energy Studies and Training (CNEST) at the Federal University of Technology Owerri

- FGN-IAEA Marine Contamination Coastal Field Monitoring Station (MCCFMS) located in Koluama.

The FGN-IAEA Marine Contamination Coastal Field Monitoring Station (MCCFMS) in Koluama serves as a monitoring entity rather than a research center. It collaborates with the Nigerian Atomic Energy Commission (NAEC) and various organizations to develop educational and training programs encompassing nuclear science, engineering, technology, and crafts. These endeavors involve the creation of new programs or the modification of existing ones. Over the past decade, the NAEC has focused on realizing the establishment of a nuclear power plant. Their target involves achieving a nuclear power capacity of 1000 MW by 2027 and 4000 MW by 2037 [7,17]. Nigeria is actively preparing for the construction of a nuclear power plant. While the NAEC has made substantial progress, including ratifying international agreements, establishing a robust regulatory framework, and collaborating with other organizations for technical cooperation, several challenges must be surmounted to attain their objectives. These challenges encompass deficiencies in electricity infrastructure, financial and political hurdles, and the need for public acceptance [17]. Consequently, Nigeria will likely commence the construction of a nuclear power plant after 2023.

In the context of uranium exploration, the now-defunct Nigeria Uranium Mining Company (NUMCO) was established as a collaborative venture between Nigeria and France to initiate uranium exploration within the country. This endeavor resulted in the discovery of uranium deposits in seven Nigerian states: Cross River, Adamawa, Taraba, Plateau, Bauchi, Kogi, and Kano. By 2001, the estimated uranium reserve stood at 200 tons, with concentrations ranging from 0.63 % to 0.9 % at depths spanning 130 to 200 meters [20]. During this period, preliminary studies were conducted to evaluate the feasibility of a uranium mining project and potential sites for nuclear power plants. These initiatives received assistance from the Bureau de Recherches géologiques et minières, a Swiss engineering consultant (Motor Columbus), and other international technical partners [20]. The progression of the national nuclear power program encountered hindrances due to a lack of clearly defined planning and, as a result, a lack of coordination among government agencies. In 2010, (NAEC) unveiled plans to assess four potential sites for nuclear power plants in different regions of the country. These included Itu in Akwa-Ibom state for the South-South region, Geregu in Kogi state for the North-Central region, Agbaje in Ondo state for the South-West region, and Lau in Taraba state for the North-East region [17]. Following further evaluation in 2015, Geregu and Itu were designated as the preferred locations by a specialized team operating under the auspices of the NAEC. In 2017, Nigeria and Russia formalized agreements for constructing and operating a nuclear power plant and a nuclear research center featuring a multi-purpose research reactor in these chosen locations [7,17].

2. METHODOLOGY

The SWOT analytical tool is valuable for evaluating the strengths, weaknesses, opportunities, and threats associated with a project or an organization. It is applicable at various levels, from personal to organizational, and serves as a beneficial instrument in decision-making processes. Through this analysis, companies can pinpoint their strengths, spot potential opportunities, and proactively address threats that could impact the feasibility and longevity of a project, business, or organization [21]. This approach holds considerable interest among researchers and garners widespread recognition among energy sector experts for energy planning. SWOT analysis has been instrumental in assessing Nigeria's nuclear exploration agenda [22] and appraising the renewable energy sector in Pakistan [23]. Additionally, the SWOT analytical tool has been employed to conduct in-depth assessments of technological advancements and the export potential of green energy for East Asian countries, including Taiwan, Japan, and South Korea [24].

Similarly, the SWOT analysis has found application in the evaluation of various facets of energy development, including comparisons between Africa's photovoltaic solar power and China's energy landscape [25], the examination of Macedonia's national energy sector concerning sustainable energy development [26], and the identification of pivotal issues and factors for attracting investors to Tunisia's renewable energy market [27]. The SWOT analysis is lauded for its advantages, including cost-effectiveness, suitability for execution by individuals with a grasp of the relevant field, and its focus on critical factors impacting the viability of a given project or business. However, it has limitations, such as the absence of alternative decision-making or solutions, a failure to prioritize issues, and the generation of excessive information without identifying the most pertinent aspects [28]. This study on the history and current status of the African nuclear industry, with a particular focus on Nigeria, holds immense significance for the Nigerian nuclear energy sector. It can serve as an invaluable resource for informed decision-making in the pursuit of Nigeria's nuclear energy agenda.

Internal factors	
Strengths (+)	*Weaknesses (-)*
• Stringent regulations governing the secure operation and management of nuclear waste • Availability of a proficient workforce and extensive knowledge of nuclear technology • Abundance of substantial uranium reserves • Limited seismic occurrence events	• Inadequate commitment to investment in the nuclear energy sector • Insufficiency in financial allocation • Limited capacity in the electrical transmission network • Deficient maintenance practices
External factors	
Opportunities (+)	*Threats (-)*
• Availability of international partners and investors • Growing global consciousness on carbon mitigation and achieving SDGs 7.1, 9.1, 11.1, and 13.1 [29], respectively • Rising energy consumption • Cross-regional connectivity	• The incoherence of energy regulations or policies that may occur due to political transitions • Corruption • Predominance of petroleum-based fuels • Poor security network and youth restiveness in some areas of the country

Table 6: An analysis of the strengths, weaknesses, opportunities, and threats associated with constructing a Nuclear Power Plant (NPP) in Nigeria. As can be seen, despite the weaknesses and threats, Nigeria exhibits considerable strengths and promising opportunities in integrating nuclear energy into its energy generation mix. The identified weaknesses and threats primarily pertain to political or managerial aspects and are deemed surmountable.

3. RESULTS AND DISCUSSIONS

3.1. Analysis of the strengths, weaknesses, opportunities, and threats for the inclusion of nuclear energy in Nigeria's energy generation mix

This section provides a comprehensive examination of particular variables examined in this study. The evaluation framework can be found in Table 2 and will be extensively discussed in subsequent sections.

3.2. Analysis of strengths

3.2.1. Stringent regulations governing the secure management and disposal of nuclear waste

The potential benefits of utilizing nuclear energy for peaceful energy needs, often weighed against concerns about nuclear weapons proliferation, particularly by anti-nuclear advocates, should not be considered a factual concern. Building and operating a commercial nuclear power reactor requires distinct expertise and knowledge different from the skills needed to develop nuclear weapons.

The global community has strongly emphasized this aspect to guarantee the peaceful utilization of nuclear energy [30]. In this regard, Nigeria has taken significant steps by establishing the Nigerian Nuclear Regulatory Authority (NNRA) to oversee and regulate its nuclear program. The NNRA is responsible for issuing licenses to individuals and organizations involved in various aspects of radioactive material and ionizing radiation, including procurement, sale, storage, import/export, use, and disposal [7].

Furthermore, in cooperation with NAEC, Nigeria has committed to adhering to various international agreements and guidelines concerning nuclear safety and waste management, including the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management. In addition, Nigeria has enacted legislation aimed at promoting the peaceful utilization of nuclear energy. These legislative measures [7] establish institutions, define civil liability, and outline the responsibilities of different government levels and stakeholders. Consequently, these regulatory laws have set Nigeria on a promising path towards constructing a nuclear power plant.

3.2.2. Access to the skilled labor force and expertise in nuclear technology

Nigeria has made substantial investments in personnel training to ensure the safe and peaceful utilization of nuclear power when it establishes a nuclear facility in the future. The country has established functional institutions dedicated to nuclear research, offering both Master's and Ph.D. programs, as discussed in the preceding chapter. With a track record of over two decades in applying nuclear technology, particularly in medical and scientific research, Nigeria has emerged as a frontrunner in this field, surpassing most African nations. Its nuclear research institutes have evolved into centers of excellence for training not only Nigerian citizens but also individuals of African descent, making them proficient in the application of nuclear technology [7,17]. It's worth noting that the author of this work has personally benefited from the investment in human resources dedicated to Nigeria's future utilization of nuclear technology.

3.2.3. Presence of large quantities of uranium reserves and allied natural resources

In principle, the availability of resources at a specific location plays a crucial role in determining the choice of energy generation technology. In the case of nuclear power, the availability of nuclear fuel, such as uranium, at a site may not be the primary factor influencing the decision to site a nuclear power plant. However, if uranium resources are present, they can have a positive impact on reducing operational costs. Nigeria is one such location with abundant uranium deposits, particularly in the country's southern region. Nonetheless, uranium's commercial extraction and production in Nigeria require significant development [7,20]. The Nigerian government has expressed interest in harnessing its uranium resources, although concrete steps toward exploring these vast deposits are yet to be taken. To expedite progress in this regard, the government has been actively seeking investors willing to participate in the investigation and development of the uranium sector. Nigeria boasts a wealth of natural resources, including [7,11]:

- **Crude oil:** Nigeria ranks among the top oil producers in Africa and is a major exporter of petroleum products to the global market.
- **Natural gas:** Nigeria boasts substantial reserves of natural gas and is reckoned to be a major exporter of liquefied natural gas (LNG).
- **Solid minerals:** Nigeria is endowed with abundant reserves of diverse minerals, including coal, tin, iron ore, limestone, lead, zinc, and many others.

The abundant reserves of natural resources, with the incorporation of nuclear energy into Nigeria's energy generation mix, are poised to bolster the nation's economic sustainability significantly.

3.2.4. Limited seismic occurrence events

Seismic activity in Nigeria has been documented only from the early 20th century onwards, with recorded earthquakes dating back to that period [31,32]. During the early 1900s, several moderate-sized earthquakes were reported in the northern part of the country. As we moved into the mid-20th century, Nigeria experienced a series of damaging earthquakes, including a magnitude 6.0 earthquake in 1960 that inflicted substantial damage on the northern city of Kano. In 1991, a magnitude 5.5 earthquake struck the eastern city of Calabar, leading to widespread damage and multiple fatalities [31]. Notably, these recorded seismic events primarily occurred in Nigeria's northern region, which has never been considered a suitable location for the siting of nuclear power plants in Nigeria. As previously discussed, the proposed sites for establishing a nuclear power plant in Nigeria have no history of seismic events. They are situated far from the earthquake-prone zones in the north and west. This makes these regions of the country more suitable for siting a nuclear power plant.

Choosing a site free from the threat of severe earthquakes is paramount when considering building a nuclear power plant. A comprehensive assessment of the geological conditions at potential locations must be conducted, employing advanced engineering tools, to avert potential disasters during the construction and operation of a nuclear power facility. Fortunately, Nigeria is relatively low risk regarding earthquakes, as most of its landmass is situated in areas not prone to seismic activity [32]. Consequently, it is entirely viable to pursue the construction of a nuclear power plant. Drawing from the lessons garnered from the catastrophic nuclear accident at Fukushima Daiichi in 2011 [19,33], it is clear that modern nuclear power plants are meticulously engineered to withstand specific levels of seismic activity, enhancing their safety and resilience.

3.3. Weaknesses analysis

3.3.1. Lack of adequate investment in the nuclear energy sector

Nigeria's efforts in integrating nuclear energy into its energy portfolio have encountered persistent delays primarily stemming from inadequate government investment and a lack of commitment from influential stakeholders. The recurring lack of substantial financial support from successive administrations has significantly hindered progress [8,11,22]. It is imperative to garner public support to advance the cause of establishing a nuclear power plant, as any disunity or lack of consensus within the general populace could pose a significant obstacle. Therefore, it is crucial to facilitate an extensive nationwide discourse regarding introducing nuclear facilities, resulting in a collectively binding decision that transcends changes in government. This unified national consensus can also serve as an enticing factor for potential investors to channel their resources into nuclear energy, thereby ensuring its sustainability during political transitions.

3.3.2. Inadequate electrical (transmission) network
Establishing a nuclear power plant for electricity production requires careful consideration of its implications for the grid system's design, operation, and stability. However, Nigeria's electricity grid faces a plethora of challenges. Recent research indicates that over the past decade, the country has suffered a staggering 50 % loss of the total electricity generated, primarily due to issues in transmission and distribution. Of these losses, 5 % can be attributed to transmission problems, while the remaining 45 % result from distribution and commercial inefficiencies [34]. The root cause of these challenges lies in the outdated nature of the grid system's infrastructure. Therefore, authorities must consider these challenges, as the grid system's existing characteristics can influence the reactor size or capacity selection when constructing a nuclear power plant.

Hence, Nigeria's electricity grid system must undergo substantial enhancements and expansion to accommodate the successful implementation of a nuclear power plant. Without these upgrades, adding a nuclear power plant could pose risks to the plant itself and the country's overall electricity system, potentially jeopardizing its safety and operational efficiency.

3.3.3. Insufficient financial budget
Nuclear energy is characterized by a substantial initial investment cost, rendering it particularly susceptible to fluctuations in interest rates. While construction costs can vary depending on the project and location, the cost per kilowatt typically remains higher than conventional energy sources such as natural gas [36]. In the case of developing countries with a relatively high GDP-to-debt ratio, the financial resources required to finance the construction of a nuclear power facility independently can be substantial due to limited borrowing capacity. While the private sector's involvement in funding such projects is rising, government support remains pivotal in securing the necessary funding for a nuclear power plant. According to the International Monetary Fund (IMF), Nigeria's current debt level of $98.6 billion presents a formidable challenge in allocating sufficient funds for a nuclear power plant project, especially amid other critical and immediate economic priorities.

3.3.4. Lack of proper maintenance practice
Emphasizing the significance of maintenance is vital for achieving quality management and optimal output. It is imperative to ensure the continued functionality and productivity of critical assets. Poor maintenance practices are not limited to Nigeria but are prevalent in various developing economies. However, such a culture is unacceptable within the nuclear energy sector, given the stringent safety requirements it demands. Assessing a country's safety culture is pivotal in determining its preparedness to integrate nuclear energy into its energy mix. Enhancing safety practices through the study of safety principles can substantially improve the overall safety performance of a nuclear facility [37]. Given the potentially catastrophic consequences even minor errors can have in using nuclear energy, Nigeria must prioritize

improving its maintenance culture as a prerequisite for incorporating nuclear power into its energy mix.

3.4. Opportunities analysis

3.4.1. Availability of international partners and investors

Nigeria's plan to integrate nuclear energy into its electricity generation has garnered significant international attention. According to Professor Ahmed Yusuf, Chairman and CEO of the Nigeria Atomic Energy Commission, as revealed in a "Nuclear Business Platform Hotseat Interview" [38] discussing the latest developments and prospects of Nigeria's nuclear energy initiative, countries like Russia, France, and China have expressed a keen interest in constructing a nuclear power plant in Nigeria. These nations are eager to collaborate with the Nigerian government to materialize the nuclear energy project.

3.4.2. Growing global consciousness on carbon mitigation and achieving Sustainable Development Goals (SDGs)

The demand for an eco-friendly energy system has become a worldwide issue. All governments are looking for ways to generate energy with fewer harmful environmental impacts for present and future generations. This has led to discussions about incorporating nuclear energy into different countries' energy sources. Many African countries, including Nigeria, are taking steps towards implementing nuclear power to reduce pollution levels and achieve the Sustainable Development Goals related to “access to energy, sustainable industrialization, sustainable cities and communities, and climate action” [29].

3.4.3. Rising energy consumption

Nigeria's energy needs have significantly increased in the last several years. The population is rising at a pace of 4 % annually, and the forces of industrialization and urbanization, which have grown at an average rate of 12 % between 1980 and 2015, are liable for the spike [3,7]. Notably, over the last ten years, the electricity demand has increased at an annual growth rate of more than 20 % in several sectors, including commercial, industrial, and residential. As a result, this surge has placed a tremendous strain on Nigeria's electricity generation infrastructure. Notably, the country had a startling 100 % rise in the energy growth rate and a 55% increase in peak energy demand between 2000 and 2015 [3,7]. The commercial and residential sectors have had the highest growth rates, possibly linked to increased per capita income, greater grid connectivity, technological advancements, and higher salary structures for the working population [5]. As the incomes of individuals rise, they tend to transition from burning biomass to cleaner energy sources like electricity for domestic cooking. This change has resulted in a significant increase in electricity demand, driving development in the electricity industry.

Nonetheless, a significant portion of the Nigerian population still needs access to environmentally friendly energy resources; incorporating nuclear energy can bridge this gap and provide electricity to these households and businesses. Furthermore, nuclear power plants are often regarded as highly suitable for meeting "base load" energy demands because of their particular features, which include a constant output, longer fuel cycles, high-capacity factors, and restricted ramp-up and ramp-down capabilities. Furthermore, nuclear power plants are often regarded as highly suitable for meeting "base load" energy demands because of their particular features, which include a constant output, longer fuel cycles, high-capacity factors, and restricted ramp-up and ramp-down capabilities. The term "base load" alludes to a continuous and stable demand for electricity that exists around the clock, often at a reasonably uniform rate. Base load power plants are precisely built to offer an uninterrupted and reliable electricity supply that meets this regular demand. Nuclear power reactors are designed with these features in mind, making them a dependable source to meet the grid's increasing electricity demand.

3.4.4. Cross-regional connectivity

Nigeria currently participates in two significant regional power pools within the West African region: the West African Power Pool (WAPP) and the North Core Power Transmission Company (NCP) [5, 7]. These memberships enable Nigeria to transmit and export electricity to its neighboring countries.

1. **West African Power Pool (WAPP):** The WAPP encompasses 14 countries in West Africa, including Nigeria, with the primary aim of advancing power system integration and enhancing electricity accessibility within the region. Nigeria is the largest electricity producer within WAPP and actively exports electricity to neighboring countries. Notably [7,34]:

- **Benin:** Nigeria facilitates the export of approximately 200 MW of electricity to Benin through a 330 kV transmission line connecting both nations.
- **Niger:** Nigeria exports about 20 MW of electricity to Niger through a 132 kV transmission line that interconnects the two countries.
- **Togo:** Nigeria transmits about 50 MW of electricity to Togo via a 330 kV transmission line connecting the two countries.
- **Burkina Faso:** Nigeria has plans to export electricity to Burkina Faso by constructing a new 330 kV transmission line.

2. **North Core Power Transmission Company (NCP):** The NCP encompasses five West African countries, including Nigeria, and shares similar objectives with the WAPP in terms of promoting power system integration and improving regional electricity access, as indicated in [7, 35]. Within the NCP, Nigeria exports electricity to one neighboring country:

- **Niger:** Niger benefits from a power export of around 20 MW from Nigeria through a 132 kV transmission line connecting the two countries, as indicated in reference [3].

It is important to highlight that Nigeria has encountered various challenges in its electricity interconnections with neighboring countries, ranging from transmission infrastructure issues to payment concerns for the supplied electricity. Despite these obstacles and the country's electricity sector difficulties and supply shortages, Nigeria has continued exporting electricity to neighboring nations.

NEPIO, the organization tasked with implementing Nigeria's nuclear energy program, is poised to assess the nation's power grid and its connectivity within the West African Power Pool (WAPP). This evaluation aims to develop a robust strategy for exporting nuclear energy to the WAPP region. It offers a significant opportunity to advance Nigeria's nuclear energy initiative while enhancing the integration of the regional power system.

3.5. Threats analysis

3.5.1. The incoherence of energy regulations or policies that may occur due to political transitions

While many African countries have formulated energy policies to bolster their energy sectors, these policies are vulnerable to domestic and foreign influences, making their consistent implementation a formidable challenge (39). Moreover, the uncertainty surrounding policy execution, stemming from changes in political leadership, poses a substantial risk to large-scale undertakings, such as constructing and developing nuclear power plants. This predicament is particularly acute in the case of Nigeria, where initiatives launched by previous administrations have been left in limbo after changes in government. This discontinuity not only hampers progress, especially in a financially constrained nation striving to optimize its resources but also elevates the risk profile for financing major investments, thereby dissuading potential investors from engaging in the nuclear energy market.

3.5.2. Corruption

According to Transparency International, corruption entails the abuse of entrusted authority for personal gain (40). This unethical conduct extends beyond public officeholders, encompassing private individuals granted access to political power or secular authority. A clear example of corruption is a public official accepting bribes in exchange for awarding a contract to a particular supplier. In the nuclear industry, the secular authority tied to access to sensitive information, technology, and materials falls under entrusted power. Despite often being overlooked, corruption emerges as a pivotal factor in nuclear proliferation. Research findings indicate that, except for North Korea, nearly all recent instances of nuclear weapons programs conducted by terrorist groups or states were facilitated by corrupt individuals or spies [41]. The success of nuclear proliferation often pivots on acquiring information obtained through unethical means involving insiders and outsiders tainted by corruption.

Corruption exerts a substantial impact on the potential for nuclear weapons proliferation. It significantly influences the initial project costs, consequently affecting the LCOE for such an energy system [42]. This influence stems from the tendency for projects to be assigned through restricted bidding procedures or single-sourced contracts rather than open and transparent bidding processes, often resulting in inflated project expenses. Many of these projects tend to be awarded to associates through dubious means, thus escalating the overall cost of energy production. Regrettably, the world has long been grappling with corruption. Transparency International's publication [43] reveals Nigeria's unfavorable Corruption Perceptions Index, attributing its global advancement challenges and painful predicament to corrupt practices primarily perpetuated by some political leaders, often with clandestine support from unscrupulous international networks and cabals. The consequences of corruption serve as formidable obstacles to the nation's progress and the successful realization of significant undertakings such as constructing and maintaining a nuclear power plant. This situation has understandably raised concerns among investors across various industries. Addressing this issue necessitates a collective effort, not just from upright individuals within the government but also from all citizens, to ensure conducive conditions for implementing and operating the nuclear power project, thereby fostering both development and peaceful processes.

3.5.3. Predominance of petroleum-based fuels

Nigeria's energy policies exhibit noticeable favoritism towards fossil fuels, creating a substantial hurdle for accepting alternative energy sources. To illustrate, the Nigerian government extends subsidies to bolster the usage of fossil fuels. However, nations must transition away from fossil fuels towards cleaner energy alternatives to mitigate the detrimental environmental effects of greenhouse gas emissions. According to the International Energy Agency (IEA), eliminating fossil fuel subsidies could lead to a 5 % reduction in greenhouse gas emissions. These subsidies disrupt the market dynamics and hinder the growth of alternative energy sources, thus curtailing the potential for essential investments [3]. In addition, there is a prevailing tendency among policymakers and decision-makers to prioritize immediate economic growth at the expense of long-term sustainable development, which discourages investors and business leaders from exploring uncharted territories [25].

3.5.4. Poor security network and youth restiveness in some areas of the country

When considering introducing nuclear energy in developing nations, the primary focal point revolves around safety and security issues. Of particular concern are the porous borders prevalent in many of these countries, Nigeria being a prime example, which presents a notable vulnerability due to the multitude of potential entry points that might allow unvetted individuals to gain access. This concern is exacerbated by the fact that neighboring countries such as Burkina Faso, Sudan, Niger, and Cote d'Ivoire have significant terrorism-related challenges, adding a layer of complexity to the security dilemma. Furthermore, the necessity for local expertise to operate a nuclear facility effectively compounds the situation, raising questions about the availability of such expertise. Despite Nigeria's established background in nuclear research, pervasive skepticism persists regarding the likelihood of accidents and the catastrophic repercussions they could entail.

African countries, Nigeria inclusive, need substantial improvements in their security infrastructure to keep pace with the rapidly advancing technological, scientific, and commercial landscape where instances of criminal activities occur [44]. Hence, Nigeria must take significant strides in bolstering its security measures, particularly in anticipation of the potential integration of nuclear energy into its energy mix. To achieve this, it becomes imperative to educate the general populace, particularly residents in border regions, to remain vigilant and promptly report any suspicious activities to the relevant security authorities. The Nigeria Immigration Service also plays a pivotal role in ensuring that only individuals meeting the necessary criteria are granted entry into the country; hence, there is a need to provide them with adequate training and resources to carry out their duties efficiently. Furthermore, it becomes imperative to modernize and equip the Nigerian police and intelligence units for effective monitoring and prevention of potential smuggling or trading of items related to the proliferation of illegal goods at the nation's borders.

3.6. Financing Options, Energy Policy & Structure

3.6.1. Financing options for the building of a nuclear power plant in Nigeria

Developing nations worldwide have long grappled with securing financing for nuclear power plant projects. Over the past few decades, the landscape of financing for these large-scale endeavors has experienced significant transformations. Various financing options are at the disposal of the Nigerian government for consideration in the construction of a nuclear power plant:

- ***Contractual long-term electricity arrangements*:** This model revolves around establishing consistent revenue streams for a Build-Own-Transfer (BOT) or concession project of an independent power plant, facilitated through a Power Purchase Agreement (PPA). A PPA ensures enduring contractual arrangements for electricity production. These agreements are typically forged between an independent power producer (in this context, a nuclear power entity) and a purchaser, commonly a state-owned electricity utility in the nation where the nuclear power plant is intended to be sited [45]. An instance of this model is the Akkuyu nuclear power plant in Turkey, where the Turkish Electricity Trade and Contract Corporation (TETAS) committed to buying electricity at a fixed rate of 12.35 cents per kilowatt-hour for a 15-year duration. The revenue derived from the PPA is anticipated to underwrite the project's expenses [36].

- ***Bilateral partnership*:** This approach entails project implementation through government-backed arrangements, usually involving loans or the provision of nuclear technology expertise. Its success hinges on the level of collaborative engagement between the participating governments. This avenue allows the host country to gain technical proficiency in nuclear energy from the partner country, particularly if the partner possesses pertinent knowledge and is amenable to sharing it. Moreover, it enables the exporting country to market its products and knowledge to other nations, ultimately resulting in mutual benefits for the participating countries [46].

- ***Vendor sponsorship:*** This refers to "vendor financing" and a situation whereby a vendor extends financial aid to a customer. The customer can then use borrowed funds to acquire the vendor's products or services [47]. This arrangement can take various forms, including "vendor equity," "vendor-arranged credit," or "vendor-provided credit" [47, 48]. The feasibility of vendor financing depends on the vendor's financial stability and market demand. A notable example of vendor financing is the Hungarian New Paks Project, funded by ROSATOM through a 30-year interstate loan. This project encompasses constructing two units of Russian reactor-type VVER with a combined capacity of 2,400 megawatts. The loan repayment period spans 21 years, covering 80 % of the project's estimated total cost [36].

3.7. The Energy Policy and structure of Nigeria's electricity sector

The Energy Policy of Nigeria in 2003 was established to ensure that all Nigerian citizens have access to dependable, cost-effective, and sustainable energy services. Subsequently, this policy underwent a revision and update in 2015, featuring several key objectives. These objectives encompass the enhancement of energy security, the promotion of energy efficiency and conservation, and the augmentation of the proportion of renewable energy within the nation's energy portfolio [3,7,11].

The structural framework of Nigeria's electricity sector has undergone a series of changes over time. The Power Holding Company of Nigeria (PHCN) was primarily responsible for electricity generation, transmission, and distribution until it underwent a significant restructuring in 2013. This restructuring led to the emergence of the Transmission Company of Nigeria (TCN) and the establishment of 11 distribution companies (Discos) alongside six generation companies (Gencos). The inception of the Discos occurred due to PHCN's unbundling, and their responsibility lies in distributing electricity to households and businesses within specific geographical zones in the country. Simultaneously, the Gencos were also instituted in 2013, bearing the vital role of electricity generation [7].

The Nigerian Electricity Regulatory Commission (NERC), established in 2005 as mandated by the Electric Power Sector Reform Act (EPSRA), assumes the regulatory authority over Nigeria's electricity sector. NERC's purview encompasses regulating electricity generation, transmission, distribution, and trading within the country. This sector is structured into three distinct segments [7]:

- **Generation:** Within this sector reside the Nigerian National Integrated Power Project (NIPP), the Niger Delta Power Holding Company (NDPHC), and independent power producers (IPPs).
- **Transmission:** This segment carries the responsibility of high-voltage transmission, facilitating the movement of electricity from the generating companies to the distribution companies.
- **Distribution:** The distribution segment, conversely, handles the distribution of low-voltage electricity to households and businesses. Nigeria boasts 11 distribution companies, each entrusted with serving specific geographic regions.

The Nigerian government is actively engaged in expanding electricity access to its citizens while concurrently enhancing the efficiency and sustainability of the energy sector. These initiatives encompass augmenting the proportion of renewable energy sources within the national energy mix, bolstering the grid's reliability, addressing challenges associated with electricity theft and bill non-payment, and formulating plans for integrating nuclear power into the energy mix [2,5,7,22].

4. SOUTH AFRICAN NUCLEAR INDUSTRY

4.1. Status of the nuclear industry in South Africa

The nuclear sector in South Africa has been a subject of significant debate and promise, primarily owing to the nation's abundant uranium reserves and its substantial energy demands. This session seeks to objectively assess South Africa's nuclear industry, analyzing its current status, benefits, challenges, and outlook for the future.

The issue of energy security in South Africa has been a subject of prolonged discussion. Prior to the end of apartheid in 1994, the nation faced significant international economic sanctions, leading the government to rely heavily on domestic resources, particularly coal, to meet its energy demands. These economic restrictions also played a pivotal role in the South African government's inclination towards developing a nuclear power sector. The only nuclear power station, Koeberg, situated in the Western Cape near Cape Town, commenced operations on the 14th of March, 1984, and has continued to operate ever since. With the dawn of democracy in 1994 and the consequent lifting of economic sanctions, South Africa became more open to importing alternative energy sources like oil and gas. This was intended to complement the coal sector, which had a substantial energy demand, and to diversify the country's energy mix.

Despite these initiatives, coal has remained the predominant energy source in South Africa. However, coal has become progressively less viable as an energy source due to its inefficiency and its pronounced CO_2 emissions that contribute to global warming. In 2008, widespread power outages and South Africa's commitment to reducing greenhouse gas emissions reignited interest in nuclear power generation [50].

4.2. Overview of South Africa's Energy Mix

South Africa has experienced relatively stable energy provision for several decades now. While the country had to rely heavily on its domestic energy resources during the apartheid era due to economic sanctions imposed, it was compelled to sustain its industrial and manufacturing sectors. This energy utilization pattern persisted even after the end of apartheid in 1994 but has since become somewhat more diversified. This diversification can be attributed to the removal of economic sanctions and the introduction of oil imports, mainly from OPEC member states, and the importation of natural gas from neighboring countries.

South Africa's energy resources predominantly consist of coal (67 %), oil (19 %), solid biomass and waste (10 %), natural gas (2 %), nuclear (2 %), and hydroelectric power (less than 1 %) [51]. In terms of energy consumption, the sectors can be categorized as follows: the industrial sector accounts for 45 %, transportation for 20 %, and non-energy resources, which includes the use of coal, gas, wood, and oil for the production of chemicals and paper, comprise 17 %, residential consumption stands at 10 %, agriculture at 3 %, commerce at 3 %, and other sectors collectively make up 2 % [52].

Analyzing the figures mentioned above, it becomes apparent that the industrial sector takes the lead in energy consumption within South Africa, contributing to roughly 50 % of the total energy usage, with a particular emphasis on manufacturing activities. Nevertheless, due to policies implemented by the government, ensuring electricity access to residential areas and providing a reliable power source for all South Africans has been prioritized. This shift in focus has, in turn, exerted substantial strain on the national electricity grid, leading to prevalent power shortages and outages throughout the country [51, 52].

Despite the persistent challenges of energy shortages and insufficient power generation, South Africa relies heavily on coal as its primary energy source. The nation boasts the ninth-largest coal reserves globally [53]. In 2011, South Africa witnessed the extraction of roughly 282 million short-tons (MMst) of coal, with a consumption of 210 MMst. These coal supplies were predominantly sourced from the Witbank, Highveld, and Ermelo regions in the northeastern part of the country (as indicated on the map) [54].

The post-apartheid era and the extensive coal mining operations presented an opportunity for Sasol, a prominent indigenous energy company founded in 1950, to pioneer the development of an innovative fuel derived from coal. Sasol's breakthrough lies in its ability to convert coal into liquid fuels, thereby contributing to approximately 30 % of South Africa's diesel and gasoline consumption [55]. Consequently, coal mining has become indispensable in meeting South Africa's energy security needs.

South Africa's heavy reliance on coal is primarily driven by its abundant coal reserves, expanded mining capacity, and the increasing demand for synthetic fuels. Coal is dominant in the country's electricity generation and primary energy needs, constituting approximately 90 % of power generation and fulfilling 77 % of primary energy requirements [56]. This substantial reliance produces 243,412 gigawatt hours (GWh) of energy from coal and peat sources [57]. Unfortunately, this dependence on coal has significant environmental consequences, contributing to South Africa's status as one of the world's largest CO_2 emitters and responsible for over 90 % of Africa's total CO_2 emissions [58].

Despite the adverse environmental impacts, the likelihood of a substantial shift away from coal in South Africa's energy mix in the coming decade remains low. This reluctance to transition arises from the dearth of viable alternative energy sources and the considerable costs of moving from coal to an alternative energy grid.

During the apartheid era, South Africa embarked on a significant nuclear energy development program to address its energy and security needs. In the early 1960s, the Pretoria government initiated the construction of South Africa's only nuclear power facility, located in Koeberg on the western coast of Cape Town. Two reactors, sourced from France, were installed at the Koeberg plant and became operational in 1984 and 1985, respectively [59]. The Koeberg power station currently contributes just 6 % of South Africa's overall energy production. In terms of nuclear energy, it provides 1840 megawatts of electricity (MWe), while coal-based power production stands at 38,000 MWe [60].

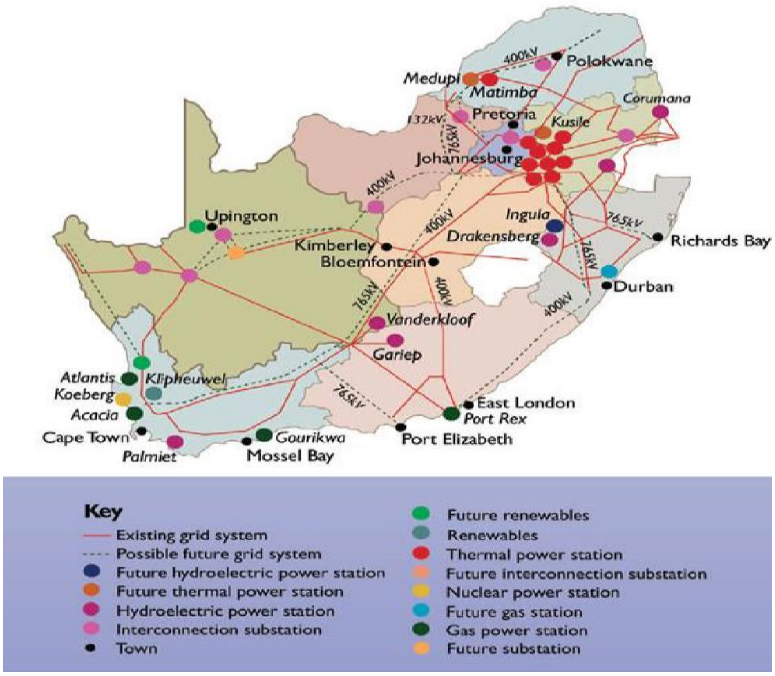

Figure 7: South Africa's power station locations [61].

Over the past two decades, South Africa has actively pursued the expansion of its nuclear energy capabilities. Since 1998, the country has attempted to make notable strides in nuclear technology, mainly through trying to develop the Pebble Bed Modular Reactor (PBMR). This innovative reactor promises to bolster energy production and efficiency, a critical consideration for South Africa's electricity sector. The sector is currently under strain due to a significant surge in demand and electrification across the nation [60]. Regrettably, the South African government has yet to bring the implementation of the PBMR to completion.

Moreover, recent statements from the South African government underscore their intention to bolster the nuclear energy supply. Their strategy involves the deployment of a new fleet of reactors, aligning with the objectives laid out in the 2010 Integrated Resource Plan (IRP) [62]. The IRP aims to introduce an additional 9,600 MW of nuclear energy into the national electricity grid by 2030, aimed at minimizing South Africa's heavy dependence on coal as its primary energy source [63]. However, the construction of nuclear power plants under this policy has faced criticism within certain academic circles. Concerns have been raised regarding the costs incurred and the lack of transparency in the procurement process [64]. Furthermore, objections have been voiced regarding the policy's disregard for alternative green energy sources, such as wind and solar power. These sources could be effectively harnessed, particularly in South Africa's coastal regions with abundant wind resources and the Northern Cape province, which enjoys ample sunlight.

4.3. South Africa's Advancements in the Pursuit of Energy Supply and Stability

Since 1994, South Africa has undergone significant changes in its domestic energy policy to address the pressing issue of providing electricity to the entire nation, with particular attention to urban and rural areas that previously lacked access to this vital resource. Central to these efforts, the 1998 White Paper on Energy Policy has played a pivotal role in guiding the government's energy-related initiatives. This document delineates a range of goals, encompassing the enhancement of affordable energy services, the improvement of energy governance, the promotion of economic development, the mitigation of environmental and health impacts associated with energy production, and the establishment of a diversified and secure energy supply (65). These goals have been intricately linked to key energy demand sectors: households, industry, commerce, mining, transport, and agriculture. Furthermore, South Africa's post-1994 energy policy agenda has extended to a variety of energy sources and sectors, encompassing electricity, nuclear energy, oil, liquid fuels, gas, coal, renewable resources, and low-carbon transition fuels, hence forming the bedrock and overarching framework for South Africa's energy policy in the post-1994 era.

Significant strides have been made in formulating and implementing various policies in pursuit of these goals; progress was achieved in developing and implementing different policies. In 2003 and 2005, Integrated Energy Plans were instituted, followed by a proposed Integrated Energy Plan in 2012 [66]. Complementing the goals outlined in the White Paper, policies such as the Electricity Pricing Policy, Free Basic Electricity Policy, and Free Basic Alternative Energy Policy were introduced to provide affordable or cost-free electricity to disadvantaged households nationally. To regulate electricity consumption and establish a national regulatory authority responsible for implementing acts like the "Electricity Regulation Act" and the "Electricity Regulation Amendment Act," additional electricity-related laws were enacted [67]. In 2008, the National Energy Act and an Energy Efficiency and Demand Side Management Policy were enacted to create a robust energy efficiency strategy. These policies were designed to manage energy consumption intensity across various sectors by addressing supply and demand. Furthermore, several acts were put in place to bolster this initiative, including the National Act of 2001 (Act 48) and its corresponding regulations, as well as the Levies Act of 2002 (Act 75), which specifically focused on natural gas. A pivotal development occurred in 2003 when a White Paper on Renewable Energy Resources was published, aligning with the Reconstruction and Development Programme of the post-apartheid government. This paper acknowledged the vast potential of renewable energy sources, encompassing wind, biomass, hydro, solar, wave energy, ocean currents, and energy derived from waste. These renewable sources played a crucial role in mitigating the environmental and health repercussions of carbon-emitting energy sources while ensuring a diversified energy supply [68].

On February 16, 2005, South Africa became a member of the United Nations - Kyoto Agreement and officially approved to contribute to reducing greenhouse gas emissions in the future [69]. Recognizing the country's substantial reliance on coal within its energy sector, the government has proactively initiated measures to curb CO_2 emissions. However, it is of concern that the 2003 White Paper on Energy Policy explicitly underscores the lack of regulatory oversight in the coal industry, a sector of paramount importance to South Africa's energy needs and overall development.

The impact of policies stemming from adopting the 2003 White Paper on Energy is palpable in several areas. A prominent example is the remarkable strides in extending electricity access to the South African populace. By 2010, over 75 % of South Africans had electricity, a substantial increase from 66 % in 2001 [70]. Furthermore, there have been noticeable changes in the energy sources utilized within the sector. A comparative analysis of the energy landscape of 2000 reveals a marked improvement in diversity. Previously, coal dominated the energy mix at 79.8 %, followed by petroleum (9.8 %), biomass (5.5 %), nuclear (3.3 %), and gas (1.5 %). Interestingly, hydroenergy was not even a factor then [71]. These advancements bear significance as they align with the objectives outlined in the White Paper. Thus, implementing various regulatory policies and control mechanisms has effectively realized specific goals.

South Africa's failure to effectively implement energy efficiency measures has caused it to lag behind many other countries globally, resulting in per capita electricity consumption that is nearly double the global average (World: 2,343 kWh; SA: 4,533 kWh). This inefficiency has also translated into higher CO_2 emissions, with South Africa emitting 2.54 kg of CO_2 for every 2,000 US dollars of GDP. In contrast, the European Union emits only 0.38 kg, Latin America and the Caribbean emit 0.59 kg, the OECD emits 0.43 kilograms, and Sub-Saharan Africa emits 1.53 kilograms [72]. Despite substantial progress in post-apartheid South Africa, including enhanced electricity access for urban and rural populations, improved energy governance and regulation, and a more diverse energy consumption mix, these advancements have been marred by significant inefficiencies. Notably, this inefficiency was exemplified by the rolling blackouts experienced in 2008 and 2022 due to strain on the power supply sector.

Despite establishing new coal-fired power stations managed by Eskom, the national power provider, there remains a significant gap that must be addressed due to the inefficiencies associated with coal as the primary energy source. The construction of two additional coal-fired power stations, Medupi and Kusile, is expected to contribute over 9,000 MW of power [73]. However, even with both these stations in operation, conservative projections suggest that if the demand increases by a mere 4 % annually, South Africa would still need to augment its grid's capacity at a pace equivalent to constructing a power station of Medupi or Kusile's magnitude every five years [74]. This concern was underscored in the president's 2014 State of the Nation address, where he outlined the government's intention to build a third coal-fired power station known as Coal 3 [75]. The president contended that with this additional power generation, South Africa could meet the growth targets of 5 % outlined in the National Development Plan (NDP). Nonetheless, Dipuo Peters, a former Energy Minister, has recognized that relying on coal-fired facilities as the primary energy source is unsustainable in the long term, primarily due to the locations of many of these plants [76]. Consequently, diversifying the energy mix in the power grid has become a paramount consideration for the South African government. Consequently, they have initiated the construction of a new fleet of nuclear reactors to achieve the 2030 objective of generating 9,600 MW of electricity from nuclear energy.

4.4. South Africa’s Nuclear Energy: The Chronicle, Ventures, Regulations, and Future Prospects

South Africa's pursuit of nuclear technology can be attributed to two primary drivers: the need for energy self-sufficiency and a government-driven endeavor to bolster its international image, particularly during the apartheid era. The Koeberg nuclear power plant was established to address these imperatives, featuring two pressurized water reactors (PWRs) with a combined power output of 1830 MW. This nuclear power supply played a pivotal role in meeting South Africa's electricity demands, especially during the challenging economic sanctions and isolation from the global community in the early to mid-1980s, with the Western Cape region reaping significant benefits [77]. A key driver of the Koeberg plant's success was uranium extraction. South Africa boasts substantial uranium reserves, totaling around 261,000 tons, representing approximately 8 % of the world's uranium resources [77, 78]. After the apartheid era, South Africa relinquished a substantial portion of its nuclear resources following its commitment to the Nuclear Non-Proliferation Treaty (NPT) signed in July 1991. Nevertheless, the Koeberg nuclear plant continued its seamless operation due to its use of "low-enrichment fuel," which adheres to international standards and guidelines for the peaceful utilization of nuclear energy [79].

The primary authority responsible for overseeing and regulating nuclear energy in South Africa is the National Nuclear Regulator (NNR). This institution takes charge of all the responsibilities, assets, liabilities, and rights previously held by the Council for Nuclear Safety [80]. The history of nuclear regulation in the country began in 1948 with the establishment of the Atomic Energy Board (AEB), which later transformed into the Atomic Energy Corporation (AEC) in 1986 [81]. Over the years, it evolved into the Atomic Energy Corporation (AEC) in 1986, gaining the authority to issue licenses for nuclear activities under the Nuclear Energy Act of 1982. In 1988, an amendment to the same act led to the creation of the Council for Nuclear Safety (CNS), an independent body responsible for overseeing nuclear installations and activities involving radioactive materials to protect individuals and property from potential adverse effects of radionuclides [82]. The need for a clear demarcation between legislation supporting nuclear activities and legislation focused on safety led to the formal creation of the National Nuclear Regulator (NNR) in 1999. The NNR's core mission is to safeguard people, property, and the environment from potential adverse effects of nuclear operations. The NNR is associated with the South African Nuclear Energy Corporation (NECSA), which, under the Nuclear Energy Act No. 46 of 1999, is authorized to conduct research and development in nuclear technology, manage radioactive materials and nuclear facilities, and collaborate with individuals and institutions on related matters [83].

South Africa has established an extensive framework of laws and international agreements to regulate nuclear energy and its primary nuclear regulatory body. These measures encompass a diverse range of legal instruments, including the Hazardous Substance Act of 1973, the Convention on the Physical Protection of Nuclear Materials (PPNM) of 1980, the Safeguards Agreement of 1991, and the Non-Proliferation of Weapons of Mass Destruction (WMD) Act of 1993, which underwent amendments in 1995 and 1996. Additionally, South Africa has established significant legislation, such as the Nuclear Energy Act of 1999, the Zangger Committee of 2000, the Additional Protocol of 2000, and the National Radio-Active Waste Act of 2008 [80]. The country is also a party to international agreements, including the Pelindaba Treaty of 2009 and the Nuclear Supplier Group of 2011, fortifying its nuclear governance framework. In 2008, South Africa introduced a Nuclear Energy Policy to complement the Nuclear Energy Act of 1999, outlining specific objectives for using nuclear energy. These goals involve promoting nuclear power as a significant electricity source, setting up governance systems for nuclear energy programs, ensuring safe utilization, managing uranium ore exports for economic benefit, enhancing energy security, and reducing greenhouse gas emissions [84].

The preceding discussion highlights South Africa's efforts to ensure the safe and responsible regulation of nuclear energy. Their regulations, introduced in the late 2000s, had unintended consequences, causing power grid strain and blackouts. In response to the 2008 energy crisis, the government explored nuclear power to meet clean energy demands. Former President Jacob Zuma, who chaired the Nuclear Energy Executive Coordination Committee, emphasized this in his 2014 State of the Nation speech to ensure stable electricity generation and power supply for the country's growth objectives [85]. However, the substantial cost of nuclear projects, estimated at 1 trillion Rand ($100 billion), surpasses Eskom's financial capacity. To address this funding challenge, South Africa plans to seek investments from business partners.

The potential establishment of multiple nuclear power plants in South Africa presents intricate challenges in ensuring the country's future energy security. Nevertheless, South Africa has considerable potential to transition towards more environmentally friendly energy sources while meeting its long-term energy requirements. However, exercising caution in the decision-making process is crucial to ensure the viability of nuclear power utilization. These considerations entail addressing environmental degradation, considering safety issues stemming from past nuclear disasters such as the 2011 Fukushima Daiichi incident in Japan, the Three Mile Island incident in the United States, and the Chernobyl disaster. Furthermore, the effective management of nuclear material storage and disposal, commonly referred to as nuclear waste management, is of utmost importance. Despite these formidable challenges, nuclear technology offers a multitude of advantages.

4.5. The Benefits of Utilizing Nuclear Power, Approaches to Managing Nuclear Waste, and The Latest Advancements in South Africa's Nuclear Energy Projects

The utilization of nuclear energy offers numerous compelling advantages. Nuclear energy is environmentally friendly, comparable to renewable sources like wind, solar, hydro, and biomass. It distinguishes itself with an extended operational lifespan, as exemplified by the Koeberg reactors, which continue to function three decades after their initial activation and are expected to remain operational for 40 years. Therefore, adopting nuclear energy underscores the importance of efficiency and reducing carbon emissions. Recent times have seen the detrimental impact of coal on the environment in South Africa, leading to severe pollution in specific regions severely compromising air quality. In 2010, coal was responsible for a substantial portion of South Africa's emissions, including 87 % of CO_2 emissions, 96 % of Sulphur dioxide (SO_2), and 94 % of nitrous oxide emissions. A study conducted in 2012 by the University of Pretoria and estimated by Greenpeace highlighted the significant external costs associated with health, climate change, water, and mining for a single coal plant, such as Kusile, potentially exceeding R30 billion ($1.5 billion) annually, with the potential to double [88]. As mentioned, South Africa ranks among the world's top greenhouse gas emitters, exceeding the global average and standing alongside other developed nations. In parallel, South Africa strives for substantial economic growth to address the urgent challenge of unemployment.

Nonetheless, a significant challenge looms large. Trade unions, including the National Union of Mineworkers (NUM), believe that a gradual decline in employment is imminent. This is due to the transition towards high-skilled nuclear energy procurement, away from labor-intensive coal mining [89]. An earlier study by Greenpeace emphasizes that global coal demand is expected to diminish, primarily due to stricter carbon emission standards, as is already evident in South Africa, where annual coal production reductions of approximately 5 % have been observed. In the long run, this decline in demand would result in a reduction in job opportunities within the coal mining sector, which currently employs around 57,000 individuals, as well as in power generation. Therefore, the South African government must contemplate the feasibility of adopting nuclear energy to reduce dependence on coal. Such a strategy can serve to curb the rise in emissions while simultaneously fostering the creation of high-skilled employment opportunities and driving economic growth.

In the foreseeable future, the adoption of nuclear energy across various industries is poised to gain momentum, presenting a means to reduce our dependence on hydrocarbons for energy, thus contributing to a reduction in greenhouse gas emissions. One of the advantages of nuclear energy is its capacity to produce hydrogen, a key player in the emerging global hydrogen-based economy. Unlike the prevalent hydrogen production methods reliant on fossil fuels, nuclear energy enables hydrogen generation through nuclear reactions from water. However, the primary challenge lies in developing cost-efficient hydrogen production technologies for the global hydrogen economy [90]. This clean hydrogen has versatile applications, including its use in hydrogen-powered vehicles available worldwide and the production of synthetic liquid fuels. South Africa's proficiency in coal-to-liquid synthetic fuel technology positions it favorably to offer sustainable alternatives to traditional petroleum and diesel fuels in various economic sectors.

The South African government has implemented additional strategies to reinforce its potential for nuclear energy advancements. Throughout 2013, South Africa engaged in discussions regarding constructing six new nuclear power facilities in collaboration with various nations. Among the prospective partners were Russia, China, the United States, the United Kingdom, and, more recently, France [98]. According to former Energy Minister Dipuo Peters, establishing these six new nuclear power plants held the promise of generating an additional 70,000 job opportunities [99]. By mid-2013, Peters also confirmed that the South African government was actively considering the Eastern Cape province as a prospective location for these power plants, primarily due to its proximity to the Indian Ocean and its status as a significant energy hub [100]. Furthermore, in response to the Fukushima disaster in 2011, the South African government has implemented substantial safety measures. The National Nuclear Regulator conducted comprehensive safety assessments at the Koeberg nuclear power plant and the Safari-1 research reactor at Pelindaba, located just west of Pretoria. These assessments yielded favorable outcomes, requiring only minor adjustments to ensure safety and compliance [101].

4.6. Critiques Regarding the Utilization of Nuclear Power in South Africa

Despite the notable advantages associated with integrating nuclear energy into South Africa's energy mix to enhance its diversity, significant opposition has been to adopting this energy source. As previously mentioned, a major point of contention revolves around the potential impact on the current workforce engaged in the coal industry. Nevertheless, it is important to emphasize that the global demand for coal is dwindling, even in countries with the highest greenhouse gas emissions, such as China. Consequently, South Africa is inevitably poised to witness job losses in its coal production sector, irrespective of whether these losses stem from a reduction in global demand or the transition to alternative energy sources.

Safety concerns have been highlighted as a significant focal point. As mentioned earlier, historical nuclear accidents raise ongoing concerns among environmental protection organizations and opposition groups. A recent criticism directed at restraining nuclear development focuses on the substantial projected cost of a new fleet of reactors, estimated at R1 trillion ($51.5 billion). This financial burden exceeds Eskom's capacity, necessitating significant foreign investment attracting countries like Russia and China. However, a look into the financial aspects worthy of note is the combined expenses for constructing the Medupi and Kusile coal-fired power stations that have already surpassed R220 billion ($11.3 billion) since inception [102]. Considering Kusile remains only partially completed, cost overruns could potentially escalate to R400 billion ($20.6 billion) for building just two coal-fired power stations instead of the intended six nuclear stations. Critical thinking reveals that the expenses for four additional coal-powered stations, including Coal 3, as mentioned by Zuma, could easily exceed the projected R1 trillion ($51.5 billion) budget for the proposed nuclear fleet. In this context, the cost gap may not be as significant as some skeptics might assume.

4.7. Nuclear Industry in South Africa versus Nuclear Industry in Nigeria

Table 7 presents a detailed comparison between the South African and Nigerian nuclear industries.

	South Africa Nuclear Industry	**Nigerian Nuclear Industry**
Nuclear Energy Generation	It has a well-established nuclear energy program, with Koeberg Nuclear Power Station being the country's only commercial nuclear power plant. Koeberg has two pressurized heavy water reactors (PHWRs) and provides a significant portion of South Africa's electricity.	It is in the early stages of developing a nuclear energy program. Plans have been made to build nuclear power plants in the future to diversify its energy mix and address electricity shortages.
Uranium Resources	It possesses significant uranium resources, making it possible to support its nuclear power generation needs. The country has historically been a major producer of uranium.	Its uranium deposits, mainly in the north-central region, could potentially support its nuclear energy ambitions.
Regulatory Framework	It is regulated by the National Nuclear Regulator (NNR), which oversees safety, security, and nuclear non-proliferation.	Nigeria has established the Nigerian Nuclear Regulatory Authority (NNRA) to oversee the country's development, regulation, and safe use of nuclear technology.
International Collaboration	A member of the International Atomic Energy Agency (IAEA) and collaborates with various countries and organizations on nuclear research, safety, and technology development.	Also, a member of the IAEA and collaborates with international partners to receive support and expertise for its nuclear program.
Nuclear Ambitions	It has expressed interest in expanding its nuclear energy capacity, although progress on new nuclear projects has been slow due to financial and political challenges.	It has expressed interest in diversifying its energy sources through nuclear power but is in the early planning and development stages. The country has signed agreements with Russia and China to construct nuclear power plants. However, it might have to reconsider continuing with the Russian partnership due to recent events between Ukraine and Russia.

Nuclear Safety	It has a relatively strong safety record in its nuclear operations, with an emphasis on regulatory oversight and safety protocols.	As the nuclear program is in its infancy, a robust safety culture to ensure the safe development and operation of nuclear facilities is also under consideration.

Table 7: Comparison between the nuclear industry in South Africa and the nuclear industry in Nigeria.

In summary, South Africa boasts a well-established nuclear industry, complete with an operational nuclear power plant, while Nigeria finds itself in the nascent stages of nuclear program development in contrast. Both countries are interested in nuclear power to meet their energy needs and expand their energy mix. However, there are marked differences in the stages of development, regulatory structures, and safety cultures within their respective nuclear industries.

4.8. What Nigeria can learn from South Africa's Nuclear Industry and what can be avoided

Here are key takeaways for Nigeria from South Africa's nuclear industry, encompassing lessons to embrace and pitfalls to avoid as Nigeria advances its nuclear program

Lessons to Learn from South Africa's Nuclear Industry:

- **Establish a Strong Regulatory Framework**:
  - Nigeria can glean valuable lessons from South Africa's well-established National Nuclear Regulator (NNR) to fortify its regulatory framework. By doing so, it can enhance safety, security, and non-proliferation measures, ensuring a state-of-the-art regulatory system.
- **Emphasize Safety Culture**:
  - Nigeria must emphasize cultivating a robust safety culture within its nuclear sector, taking South Africa's commendable safety track record as a source of inspiration. The allocation of resources towards safety protocols, comprehensive training, and diligent risk management holds undeniable importance.
- **Collaborate with International Partners**:
  - Nigeria can follow South Africa's example by engaging in cooperative ventures with international organizations and proficient nuclear nations, such as South Africa's collaboration with the IAEA and other partners. Such partnerships offer Nigeria opportunities to tap into expertise, technology, and financial backing for its nuclear initiatives. Despite Nigeria's membership in the IAEA, it should explore additional partnerships with established users of nuclear energy.
- **Utilize Domestic Uranium Resources**:
  - Nigeria should harness its uranium reserves, akin to South Africa's approach, to bolster its nuclear energy ambitions. The establishment of a domestic supply chain for nuclear fuel holds the potential to elevate energy security.
- **Plan for Long-Term Sustainability**:
  - South Africa's nuclear sector has grappled with financial and political obstacles when striving to expand its nuclear capabilities. Nigeria can gain insights from this experience by focusing on crafting plans that emphasize long-term sustainability, considering the multifaceted economic and political factors that might influence nuclear initiatives.

Aspects to Avoid from South Africa's Nuclear Industry:

- **Slow Decision-Making Process**:
  - Nigeria has the opportunity to steer clear of the protracted decision-making challenges that have impeded the expansion of South Africa's nuclear ambitions. Streamlining the decision-making process and addressing bureaucratic hurdles efficiently is vital to ensure the timely development of nuclear projects.
- **Financial and Economic Challenges**:
  - Nigeria should exercise prudence in its financial commitments to nuclear projects, taking lessons from South Africa's experiences involving funding issues and cost overruns in its nuclear sector.
- **Political Controversy**:
  - South Africa's nuclear program has encountered political controversies, making it crucial for Nigeria to strive for transparency and bipartisan support in its nuclear policies and projects. This approach will help prevent unnecessary political controversies.
- **Maintaining Public Confidence**:
  - In Nigeria's pursuit of a nuclear program, a primary focus should be on upholding public confidence and promoting awareness. Ensuring that the general populace understands both the benefits and potential drawbacks of nuclear energy is crucial to avoid any possible resistance from the public.
- **Resource Allocation**:
  - Nigeria needs to exercise meticulous deliberation when allocating resources to nuclear energy, considering its place in the broader energy landscape and national development priorities. Assessing the energy sources that hold a distinct advantage within Nigeria's specific context is essential.

Nigeria stands to gain valuable insights from South Africa's experience by prioritizing the establishment of a comprehensive regulatory framework, emphasizing the cultivation of a safety-centric culture, fostering international collaborations, and making judicious use of its domestic uranium resources. It should also exercise prudence in dealing with challenges such as slow decision-making processes, financial constraints, and political controversies, all while diligently cultivating public awareness and trust in its nuclear aspirations

5. CONCLUSION AND RECOMMENDATION

Nigeria is experiencing particular challenges in its power sector, from limited capacity, inadequate policies, and insufficient financial support to manage the energy sector effectively. The government considered introducing nuclear power as a potential solution to these issues. This study examines the history of the African nuclear industry, focusing on Nigeria and in comparison with South Africa. This study aims to assess Nigeria's preparedness to incorporate nuclear energy into its energy generation mix. The assessment thoroughly analyzes the strengths, weaknesses, opportunities, and threats (SWOT analysis) crucial for realizing the goals associated with nuclear energy integration.

Nigeria is well-positioned to undertake its nuclear energy program, primarily owing to its well-established strengths in this domain. With a track record spanning decades of engagement in nuclear research and the practical application of nuclear technologies, the nation has garnered invaluable experience necessary to manage and operate a nuclear facility effectively. However, the substantial responsibility of overseeing a nuclear power plant must still be acknowledged.

Hence, formulating a comprehensive plan encompassing the training of specialized experts for each facet of facility operation assumes paramount importance. The country's nuclear energy policy must undergo steady evaluation and refinement to harness these strengths optimally.

Industry players must address the notable deficiency in maintenance culture imperative for (which has been discussed as a weakness in the SWOT analysis), particularly in intricate settings like nuclear power plants. Regular maintenance is vital to protect the facility's lifespan and the safety of individuals. To establish effective maintenance practices, creating a well-defined policy that outlines procedures and addresses deviations from them is essential. This policy should be efficiently communicated to personnel responsible for critical areas of the facility to ensure that maintenance is conducted promptly and correctly, in alignment with the established policy and strategy.

Nigeria holds a significant opportunity for establishing a viable nuclear power initiative, a point previously highlighted in the SWOT analysis under the "opportunity" section. This potential stems from the regional interconnectivity program facilitated by the West African Power Pool (WAPP), a framework that offers a platform for investors to exploit and market electricity to neighboring nations. Moreover, Nigeria's stable democratic governance provides a conducive environment to capture the attention and interest of various countries in Nigeria's nuclear energy program, making it a promising prospect for further development.

The threats highlighted are common issues encountered by developing countries. The security protocols in these nations tend to be less stringent than those in more advanced countries. This discrepancy raises concerns and doubts regarding their capacity to operate nuclear power facilities safely. The Nigerian government and other nations facing similar circumstances should engage in community education near potential nuclear plant sites to address these concerns. This educational outreach should cover the benefits and potential risks associated with such projects as well as provide reassurance that the introduction of nuclear power will not contribute to the proliferation of dangerous weaponry. It is crucial to reassure the public that introducing nuclear power will not increase the spread of dangerous weapons. This is because the safety of the people, especially those residing near a nuclear facility, cannot be overlooked. It appears increasingly likely that designating these potential nuclear plant sites and the adjacent towns or cities as security zones is necessary to address these concerns effectively.

Nevertheless, Nigeria must bolster its security and intelligence apparatus to ensure the safe establishment of a nuclear power plant. The vulnerability of the country's borders could jeopardize the secure operation of a nuclear facility, especially in light of the increasing incidents of chaos in the sub-region. Furthermore, the heavy dependence on fossil fuels poses a significant obstacle to investments in nuclear energy. Hence, this study recommends the elimination of fuel subsidies and implementing a public policy aimed at reducing the use of fossil fuels. However, before removing these subsidies, it is vital to put in place realistic measures to mitigate any short-term adverse consequences that may result from the subsidy removal.

Looking back, it's evident that South Africa faces several important issues concerning its present and future energy makeup. It is crucial to highlight that the South African government actively strives for a more varied energy mix, and many reasons drive this pursuit.

To begin with, South Africa is heavily reliant on coal for its energy production and electricity generation. This dependency on coal can be traced back to the historical isolation experienced during the apartheid era. However, in the post-1994 era, new policies have been introduced to reduce this reliance on coal. One of the key motivations for this transition is the inefficiency associated with coal-based power generation. It's widely acknowledged that South Africa consumes twice as much energy as many developed nations and even surpasses some developing countries in terms of energy consumption for industrial production. This situation places South Africa at a disadvantage, particularly in terms of efficiency and productivity. Notably, the manufacturing sector, the largest power consumer, and the electricity generation sector are particularly affected. As a result, South Africa is compelled to diversify its energy sources to enhance its competitiveness in the global business landscape.

The South African government is aware that its heavy reliance on coal for energy production has severe and lasting environmental and financial consequences. The country's current emission of greenhouse gases ranks it as a significant contributor to global climate change. Consequently, the detrimental impacts on public health, water resources, mining, and the environment will ultimately result in higher costs than continued dependence on coal-based power generation. Moreover, the proximity of coal-fired power stations, such as Kusile and Medupi, to abundant coal deposits exacerbates these issues and is likely to amplify the aforementioned adverse effects. Similarly, the exorbitant costs associated with transmitting power from its source to various sectors of the economy are economically unviable and unsustainable over an extended period.

In response to international efforts to curb greenhouse gas emissions, many developed and developing countries have witnessed a decline in coal production. With ambitions to play a significant role in global politics and lead in African affairs, South Africa is aware of the necessity to integrate cleaner energy sources into its energy portfolio. Concurrently, the diminishing global demand for coal has affected production for several years, reducing the labor force within the coal mining and power generation sectors. As a result, the South African government has undertaken a rigorous examination of strategies to diversify the country's energy resources. The aim is to foster economic growth and job creation opportunities in alternative energy domains, encompassing renewables, biomass, oil, gas, and nuclear power.

In the final analysis, the South African government faces critical decisions regarding its energy future. While renewable energy offers substantial potential to cut greenhouse gas emissions and drive economic development, it has inherent limitations in providing a stable base load capacity, necessitating an extended time frame for sustainable growth. This leaves the government with two principal alternatives: an expansion of coal-fired power plants or a heightened focus on nuclear energy as a component of diversification.

The rationale for the South African government's emphasis on nuclear energy is twofold. Firstly, South Africa already boasts a track record of nuclear expertise, exemplified by the operational Koeberg reactors that have provided a stable and efficient 5 % of the country's energy for decades. Secondly, nuclear reactors offer a base load capacity akin to coal-fired plants but with significantly reduced environmental impact. As such, the government perceives an opportunity to pursue two concurrent objectives: gradually replacing coal with alternative energy sources and reducing greenhouse gas emissions, all while meeting the critical energy demands necessary for economic growth.

The factors outlined above have positioned South Africa on the verge of acquiring additional nuclear power facilities, aiming to diversify energy sources, curb greenhouse gas emissions, ensure a reliable power supply that catalyzes economic growth, attract foreign investments, and reduce heavy coal dependence. The government has taken strides to advance this endeavor, soliciting bids from international nuclear suppliers such as Russia and China, while a notable domestic opportunity remains largely untapped. As previously noted, the unfinished Pebble Bed Modular Reactor (PBMR) would have presented significant potential in meeting South Africa's energy needs while mitigating the complexities of maintaining and operating larger reactors. This innovative reactor was projected to offer superior efficiency compared to other nuclear power generation units, lower operational costs, and simplified maintenance and operation procedures. Moreover, it captured the attention of foreign investors seeking to acquire its patents and development rights.

For the advancement of future endeavors, the South African government should redirect its attention toward exploring existing nuclear technologies rather than welcoming foreign technology through competitive bidding processes into the domestic nuclear market. A more favorable approach would be to revisit and prioritize the acquisition of funding to complete the PBMR module with subsequent replication of this process once the initial reactors are in operation. While securing initial financing for more than two reactors may pose a challenge, the subsequent benefits will become increasingly evident as these reactors commence power generation, thereby enhancing energy efficiency within South Africa. Furthermore, the South African government must consider the potential implications of importing nuclear technology. In the event that the construction companies fail to transfer skills and knowledge to the South African workforce effectively, it could lead to an undesirable dependency on imported labor for facility maintenance and ensuring the stable operation of reactors. Therefore, it is strongly recommended that the government implements measures to ensure that these contracted enterprises proficiently transmit skills and knowledge to the local workforce, thereby promoting growth within the sector.

An additional recommendation is not to overlook the potential of establishing a hydrogen-based economy in South Africa, similar to how the opportunity of the commodity boom was missed a few years ago. Taking swift action is paramount, as the potential rewards are pretty promising. South Africa should proactively seize the initiative instead of allowing other nations to take the lead and reap the benefits. Embracing hydrogen as a clean energy source can significantly contribute to South Africa's efforts to reduce CO_2 emissions and enhance energy security. The future of nuclear energy in South Africa may appear uncertain, but it is unmistakably positioned to play a significant role in the country's energy security.

Developing nations' successful pursuit of nuclear energy hinges on having sufficient financial resources. Thus, the study examines potential financing options that could be accessible to support the implementation of such a capital-intensive nuclear project. As previously highlighted in the analysis of weaknesses section, securing financing for a nuclear power plant has always posed considerable challenges, especially within developing countries, given the heightened uncertainty involved. However, the novel financing options being proposed are designed to mitigate these uncertainties, thereby enhancing the prospects of funding a nuclear power project in previously uncharted territories.

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