sustainability

MDPI

Review

From Potential to Power: Advancing Nigeria's Energy Sector through Renewable Integration and Policy Reform

Mohammad Awwal Adeshina [1,2], Abdulazeez M. Ogunleye [3], Habeeb Olaitan Suleiman [3], Abdulfatai Olatunji Yakub [4,5], Noel Ngando Same [4,5], Zainab Adedamola Suleiman [6] and Jeung-Soo Huh [4,7,*]

1 Division of Biotechnology, Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu 42988, Republic of Korea; mohammadadeshina1@gmail.com
2 W. P. Carey School of Business, Arizona State University, Tempe, AZ 85287, USA
3 School of Electronic and Electrical Engineering, College of IT Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; azeezsucczeez@gmail.com (A.M.O.); suleiman.habeeb16@knu.ac.kr (H.O.S.)
4 Department of Convergence and Fusion System Engineering, Kyungpook National University, Sangju 37224, Republic of Korea
5 Institute for Global Climate Change and Energy, Kyungpook National University, Daegu 41566, Republic of Korea
6 Department of Environmental Engineering, Kyungpook National University, Daegu 41566, Republic of Korea; zasuleiman5@gmail.com
7 Department of Energy Convergence and Climate Change, Kyungpook National University, Daegu 41566, Republic of Korea
* Correspondence: jshuh@knu.ac.kr

Abstract: Nigeria is a nation endowed with both abundant renewable and non-renewable energy resources. Despite its vast potential, Nigeria struggles with a consistent power supply due to various systemic issues, such as inadequate funding, infrastructural decay, corruption, technical skill shortages, and macroeconomic instability. These challenges hinder the effective harnessing and distribution of energy resources, particularly renewable ones like wind, solar, biomass, and hydropower. This study assesses the existing energy policies and their efficacy in promoting sustainable energy development towards achieving universal electricity access by 2030. It highlights the necessity for a just energy transition that integrates a substantial proportion of renewable energy into the national grid, aiming to meet up to 60% of the country's energy demands with clean sources by 2050. This transition is critical not only for energy security and reducing the environmental impact but also for fostering socioeconomic equity. Recommendations include overhauling the legal and regulatory frameworks to support renewable energy growth, particularly in off-grid areas, to ensure clean, affordable, and secure energy access. Strategic investments, enhanced infrastructure, and robust public–private partnerships are essential to overcome the current barriers and realize Nigeria's energy potential. This paper calls for a comprehensive approach that addresses both the technical and socioeconomic dimensions of the energy crisis, laying the groundwork for a sustainable and prosperous energy future for Nigeria.

Keywords: renewable energy transition; sustainable development; energy policy; socioeconomic equity

check for updates

Citation: Adeshina, M.A.; Ogunleye, A.M.; Suleiman, H.O.; Yakub, A.O.; Same, N.N.; Suleiman, Z.A.; Huh, J.-S. From Potential to Power: Advancing Nigeria's Energy Sector through Renewable Integration and Policy Reform. *Sustainability* **2024**, *16*, 8803. https://doi.org/10.3390/su16208803

Academic Editor: George Kyriakarakos

Received: 6 August 2024
Revised: 26 September 2024
Accepted: 1 October 2024
Published: 11 October 2024

1. Introduction

As Africa's most populous nation, Nigeria holds a significant position in the international energy sector. The nation is at a crossroads, facing pressing energy security and sustainability issues that necessitate a strategic shift towards renewable energy and eco-friendly alternatives, including natural gas [1,2]. To effectively expand its energy sector, Nigeria must focus on climate change mitigation and robust energy security, guided by comprehensive laws and regulations. This includes a focus on ensuring access to energy that is clean, affordable, secure, and sustainable. Despite its status as the continent's leading oil producer, Nigeria confronts regional security challenges that affect its energy production and distribution [3]. The nation's struggle with a limited electricity generation capacity and a heavy reliance on less sustainable energy sources poses significant barriers to achieving an inclusive energy transition and broader socioeconomic advancement. Addressing these challenges is crucial, and it requires the implementation of strong legal and regulatory frameworks [4]. These frameworks should foster the growth of renewable energy, particularly in off-grid areas, and reinforce commitments to energy security, environmental sustainability, and zero emissions [5].

In recent years, Nigeria has experienced significant challenges in achieving a stable and sustainable energy supply, despite its abundant renewable and non-renewable energy resources. This study aims to critically evaluate the current state of Nigeria's energy policies and the potential for integrating renewable energy sources into the national grid. Specifically, the research seeks to address the following questions:

What are the key barriers to the effective adoption and integration of renewable energy sources in Nigeria?

How effective are the current energy policies in promoting sustainable energy development?

What strategies can be employed to facilitate a just energy transition that ensures energy security, environmental protection, and socioeconomic equity?

By addressing these questions, the study aims to provide a comprehensive framework for policymakers and stakeholders to enhance the adoption of renewable energy in Nigeria.

To confront these challenges, the Nigerian government has set an ambitious goal: achieving universal energy access by 2030. Tackling both the financial and technical barriers in the energy sector, the focus is now shifting towards renewable energy sources like solar, biomass, and hydropower [6]. This shift is not just about bridging the energy gap; it is about laying the foundation for sustainable development. Incentivizing renewable energy investments, empowering rural women through improved income opportunities, fostering public–private partnerships, and heightening the awareness of clean energy technologies are pivotal strategies in this direction [2]. By promoting renewable energy and implementing supportive policies, Nigeria is positioning itself to not only overcome its energy crisis but also to catalyze economic growth and ensure a more sustainable and equitable future [5,7–9].

In tackling its energy problems, the country is confronted with a series of intricate challenges, particularly the disparity between its installed electricity capacity and the actual power generated [2]. This gap, further strained by the economic burden of importing oil despite being an oil producer, highlights the critical issues faced by over 220 million people in the country, particularly those without reliable access to energy [3]. To surmount these obstacles, there is a growing emphasis on diversifying energy resources, focusing on bolstering infrastructure and making strategic investments in renewable energy and energy efficiency [1,10]. In response to these challenges, there is a need for increased investment in energy transition technologies, a sector that has seen limited input across sub-Saharan Africa. Bridging this investment gap necessitates a collaborative approach between the government and private sectors. Efforts are being channeled towards enhancing investments in the clean energy sector, especially in renewables, to break through the financial and technological barriers. These initiatives, which include expanding rural electrification through solar generation and off-grid solutions, aim to not only provide substantial investments and savings but also to revolutionize how energy is accessed in remote areas [11]. As the shift from the reliance on natural gas towards renewable energy sources gains momentum, it becomes increasingly evident that integrating low-carbon energy resources is essential for driving economic growth, promoting sustainable development, and addressing energy security. The resolution of frequent power outages, predominantly caused by an inadequate electricity supply, is fundamental to this process, as it directly impacts the country's sustainable development and causes substantial economic losses, especially in rural communities most affected by energy shortages [12].

The shift away from hydrocarbons, which are major contributors to greenhouse gas emissions, is essential for Nigeria's economic and environmental sustainability. Embracing renewable energy sources emerges as a national imperative, leveraging Nigeria's rich endowment in solar, wind, and biomass resources [9]. These resources present a substantial opportunity for the country to lead in sustainable energy development. The nation's Renewable Energy Roadmap, a collaborative effort with the Energy Commission of Nigeria, casts light on the vast potential for renewable energy deployment through to 2050 [13]. This strategic plan underscores renewable energy's pivotal role in fulfilling energy requirements, spurring economic growth, creating employment opportunities, and meeting global climate goals. The roadmap suggests that renewable energy sources, such as solar, hydropower, and wind, could satisfy almost 60% of Nigeria's energy demands by 2050 [14]. This would mark a significant reduction in the dependency on oil and natural gas, contributing to enhanced energy security, socioeconomic development, and climate change mitigation. Investment in renewable energy infrastructure is accelerating, exemplified by initiatives like Solar Nigeria, which seeks to establish a distributed solar energy market. However, a key obstacle remains in the form of the current power infrastructure; with only about 15% of the consumed energy coming from renewables, much of it is generated by inefficient generators. Augmenting the electricity infrastructure and grid stability is crucial for curbing economic losses from inconsistent power supplies and attracting further investment. Ultimately, Nigeria's transition to renewable energy is not just imperative for meeting its energy needs; it is a cornerstone for sustainable economic growth, job creation, and tackling the multifaceted challenges of climate change.

This review paper is based on an extensive survey of the existing literature and data obtained from reputable online research databases such as IEEE Xplore, ScienceDirect, Google Scholar, and Web of Science. Key reports and policy documents from Nigerian government agencies, the International Renewable Energy Agency (IRENA), the World Bank, and other international bodies were also utilized. The literature search focused on keywords including "renewable energy in Nigeria", "energy policy Nigeria", "solar energy Nigeria", "wind energy Nigeria", "biomass energy Nigeria", and "hydropower Nigeria". Documents that specifically address Nigeria's energy sector, renewable energy technologies, policy frameworks, and socioeconomic impacts were included. Relevant data were extracted from these sources and categorized into quantitative and qualitative data. The quantitative data included statistics on the energy production and capacity, investment figures, and policy targets, while the qualitative data comprised key themes, insights, and recommendations. Descriptive statistics and trend analyses were conducted to summarize and identify patterns in the quantitative data. Qualitative data were analyzed through thematic content analysis, organizing insights into key areas, such as policy analysis, technology potential, socioeconomic impacts, and infrastructural challenges. The combined analysis of both quantitative and qualitative data provided a comprehensive understanding of Nigeria's renewable energy landscape, highlighting current challenges and potential pathways for sustainable energy development. This study aims to critically examine Nigeria's energy crisis by evaluating the vast potential of its abundant renewable energy resources alongside the effectiveness of its current energy policies. It highlights the need for a just and equitable energy transition, advocating for the integration of a significant share of renewable energy into the national grid. Furthermore, this research provides strategic policy recommendations designed to address the systemic challenges hindering Nigeria's energy sector, with a focus on achieving sustainable, secure, and inclusive energy access for all.

2. Renewable Energy Potential in Nigeria

Globally, fossil fuels satisfy 85% of the energy demand, a figure set to rise by 50% by 2025 due to population growth, economic expansion, and urbanization. However, the combustion of these fuels contributes significantly to greenhouse gas emissions, aggravating global warming and climate change, and impacting various socioeconomic factors that undermine the UN Sustainable Development Goals [15]. In Nigeria, about 70% of the primary energy consumption comes from fuelwood, with only 40% of Nigerians having access to electricity. This starkly contrasts with nations like South Africa, which, despite a much smaller population, boasts a substantially higher electricity capacity [16].

Nigeria's energy mix, depicted in Figure 1 as heavily reliant on fossil fuels with oil (33%), coal (27%), and gas (25%) dominating, is on the point of a transformative shift towards a more sustainable and renewable future. Endowed with a wealth of renewable resources such as solar, wind, hydropower, and biomass resources, the country is poised to tackle its energy crisis head-on [17]. The prospect of deploying solar photovoltaic (PV) panels over just 0.01% of Nigeria's land area to yield outputs matching millions of tons of oil equivalent showcases the vast potential of solar energy [18,19]. Wind energy, too, has promising prospects, particularly in the coastal and northern regions known for their favorable wind speeds [20]. The hydropower sector, already a contributor to the national grid, harbors considerable untapped potential along Nigeria's rivers and waterways. Small- to medium-scale hydroelectric projects could dramatically increase the energy supply, especially in areas not served by the grid [21]. Biomass energy, derived from agricultural residues, not only contributes to energy generation but also promotes more sustainable farming practices. The country's geographical diversity supports the varied potential for solar and wind renewables in the arid north and hydro and biomass renewables in the more verdant south and central regions [22]. The integration of these renewable energies into Nigeria's grid promises to meet the essential needs of its population, catalyze job creation, and boost local industries [3].

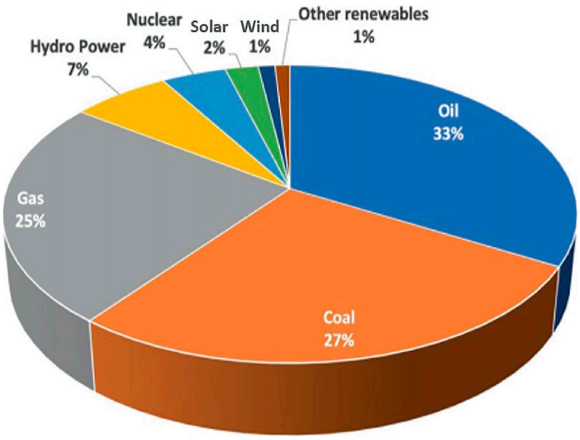

Figure 1. Sources of energy generation in Nigeria [19].

2.1. Biomass Energy Potential in Nigeria

As Nigeria strives to meet its National Determined Contributions to reduce carbon emissions and fulfill the UN SDG for affordable and clean energy by 2030, the focus on renewables, including bioenergy from organic materials like biomass, becomes increasingly important. Biomass offers a dual benefit, promoting better waste management and enhancing energy access [17,23]. It could transform Nigeria's energy framework by providing a sustainable alternative to fossil fuels, thereby fostering a greener economy and reducing the reliance on imported energy. Leveraging biomass not only supports environmental goals but also provides socioeconomic advantages by harnessing local resources for energy creation, potentially catalyzing a significant shift in Nigeria's energy paradigm towards a more stable, sustainable, and self-sufficient model [24,25].

Assessment of Available Biomass Resources

A comprehensive review of the biomass resources in Nigeria highlights the significant role of biomass as the major energy source in the country, contributing about 78% to Nigeria's primary energy supply. The study emphasizes the presence of various biomass resources, including agricultural crops, residues, forestry resources, municipal solid waste, and animal waste, all of which offer substantial opportunities for biofuel production and energy generation [22]. In Nigeria, a nation with a substantial agricultural base, the utilization of biomass for energy production presents a notable opportunity for sustainable development and energy security. Biomass is primarily derived from four key sources: agricultural waste, municipal solid waste, animal residue, and forest residue [26]. These sources collectively contribute to a significant portion of the nearly 220 billion tons of biomass produced globally each year, offering a renewable energy alternative capable of generating considerable energy with relatively low greenhouse gas emissions compared to fossil fuels. Biomass plays a crucial role in Nigeria's energy sector, contributing a substantial 78% to the country's primary energy supply. This underscores the importance of and reliance on biomass as a key energy source in Nigeria [27].

Technologically, biomass can be converted into various forms of energy and products using either thermochemical or biochemical methods, as depicted in Figure 2. Each method has distinct advantages and limitations, influenced by the characteristics of the biomass feedstock and the desired end product [28]. The potential for the commercial exploitation of biomass for electricity generation in Nigeria is significant, particularly given the high value of fuel products derived from these processes. In particular, the sugarcane industry in Nigeria, with a significant production capacity, generates bagasse, a byproduct that is a viable source for electricity generation. The estimated potential for energy generation from sugarcane bagasse is substantial, with experts indicating that Nigeria's biomass energy resources could reach 83 million tons of crop residues annually [23]. Additionally, the processing of sugar cane and other agricultural produce in Nigeria generates a significant amount of biomass, including bagasse, which can be harnessed for sustainable energy production. The Energy Commission of Nigeria (ECN) and the Nigerian National Petroleum Corporation (NNPC) recognize the diverse outputs and energy possibilities from the sugarcane industry, highlighting the potential for bioelectricity generation, fuel ethanol production, and other renewable energy applications [9]. Urban areas in Nigeria also contribute large quantities of municipal waste, which can be processed to produce biogas. This renewable fuel is used to generate green electricity and heat or is used as vehicle fuel, with the digestate from the process serving as a valuable fertilizer in agriculture [29,30].

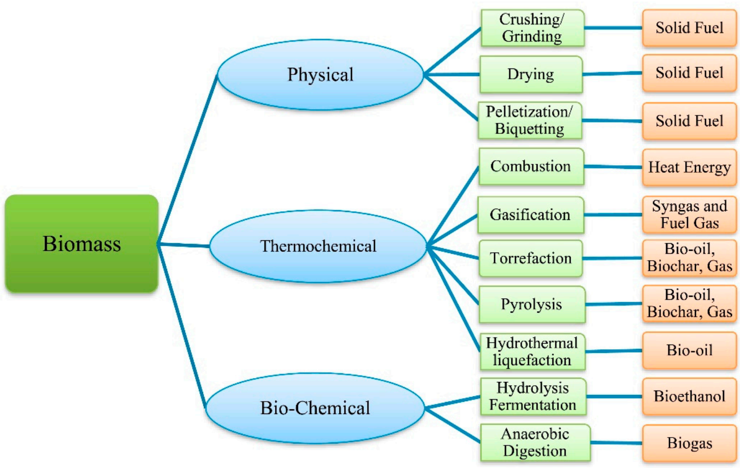

Figure 2. Biomass conversion technologies [28].

Biogas technology, while nascent in Nigeria compared to countries like China and India, is experiencing growth. The first biogas plant in Nigeria, established in 1959, processed farmyard manure. However, it was not until 1974 that the Nigerian government began significant efforts to implement residential biogas technology as an alternative energy source. The common designs for biogas plants in Nigeria include fixed domes, portable gas digesters, and small tanks or bags. The estimated national biogas potential is about 13–15 million cubic meters per day [31,32]. The opportunity to utilize biomass for biogas production is particularly prominent in Nigeria's remote regions, where community biogas plant networks can be established. With nearly 57 million animals in the country and an annual growth rate of 10%, there is ample biomass to generate over 12 million cubic meters per day of biogas. This capacity is sufficient to meet the energy needs of over 28 million people in rural areas while also producing approximately 21 million tons per day of bio-fertilizer [33].

Collaboration between the Ministry of Petroleum and Natural Resources and the Directorate General of New and Renewable Resources led to the installation of more than 4000 biogas plants between 1974 and 1987. These plants were primarily intended for lighting and cooking applications, producing about 3000 to 5000 cubic feet per day of biogas. However, the initial scheme encountered challenges such as the withdrawal of financial sponsorship by the government, high investment and maintenance costs for the technology, limited technical training, a lack of incentives, low public participation, and ineffective demonstration. The Nigerian Institute for Renewable Energy Technology Strategy, operating under the Ministry of Science and Technology, has significantly contributed to the advancement of biogas technology. In a pivotal development in 2001, the merger of the National Institute of Silicon Technology with the Photovoltaic Applied Technology Center (PCAT) led to the establishment of the Nigerian Council of Renewable Energy Technologies (NCRET). This collaborative entity has been pivotal in the widespread dissemination of biogas plants and various other renewable energy technologies across remote communities, showcasing a concerted effort towards sustainable energy solutions and technology deployment in Nigeria, as shown in Figure 3 [34].

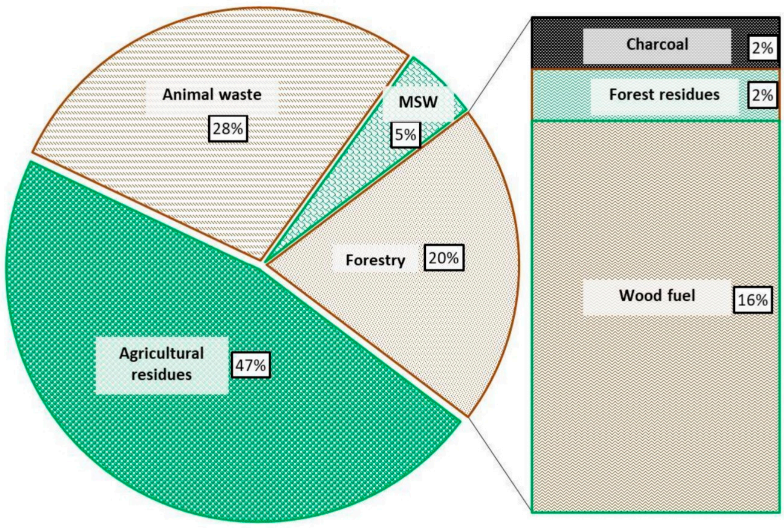

Figure 3. Contributions of biomass sources to the overall technical potential [15].

The productivity and quality of the biogas in Nigeria are greatly influenced by the type and composition of the waste used, as well as operational parameters such as the temperature, feeding rate, retention time, particle size, water-to-solid ratio, and carbon-to-nitrogen (C/N) ratio [35–37]. The optimal temperature range for high biogas production has been found to be between 30 and 40 degrees Celsius [38]. The availability of feedstock and appropriate batch loading are also crucial for the efficient operation of biogas plants and maximizing biogas yields [39]. However, the overloading or underloading of feedstock and water can adversely affect the efficiency of the biogas production process. It has been observed that, during anaerobic fermentation, carbon is consumed 25 times faster than nitrogen by microorganisms. Therefore, to meet this microbial requirement, a carbon-to-nitrogen ratio of 25–30:1 is optimal, with most of the carbon degraded within the minimum retention time. The retention time, which refers to the period the waste remains inside the digester, is typically estimated to be between 10 days and a few weeks, depending on the waste composition, process parameters, location of the plant, and atmospheric conditions.

Enhancing the digestibility of waste is vital to promote its decomposition into simpler organic and biogas products. This digestibility is usually improved through treatments using calcium hydroxide, ammonia, and sodium hydroxide, with water and urea also being effective at improving waste digestibility [15]. Utilizing biomass for bioenergy applications in Nigeria offers both economic and ecological advantages over traditional waste treatment methods. Economically, biomass serves as a cost-effective industrial fuel source, aiding in diversifying the energy mix and enhancing the energy supply. Nigeria's biofuel policy highlights economic benefits like revenue generation, job creation, improved farming practices, and reduced greenhouse gas emissions. Ecologically, biomass energy production is renewable, providing a sustainable energy option that mitigates environmental issues and reduces greenhouse gas emissions. By transitioning to bioenergy from biomass, Nigeria can address economic challenges and promote environmental sustainability, particularly in rural areas, showcasing the dual benefits of this approach.

2.2. Wind Energy Potential in Nigeria

Over the past two decades, the capacity to generate wind energy, both onshore and offshore, has significantly expanded. In 2016, wind energy constituted 16% of the renewable electricity generation. Between 1997 and 2018, the global wind generation capacity surged from 7.5 GW to an impressive 564 GW. It is evident that various regions around the world offer great potential for harnessing wind energy, with rural areas being particularly favorable. Notably, offshore wind power presents substantial opportunities [40]. Figure 4 illustrates the global trend in the installed wind energy capacity, revealing that the onshore capacity escalated from 216,345 MW in 2011 to 769,277 MW in 2021, while the offshore capacity surged from 3776 MW in 2011 to 54,257 MW in 2021, marking a remarkable 100% increase in a mere decade [40].

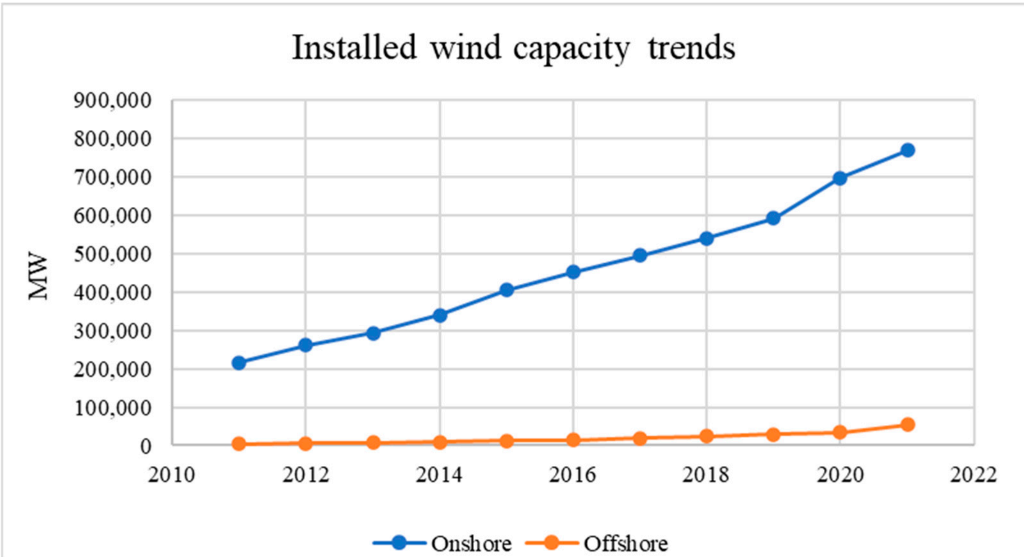

Figure 4. Global trend in installed wind energy capacity [41].

Electricity from wind energy is generated by harnessing the kinetic energy of moving air. Wind turbines or wind energy conversion systems play a pivotal role in this process by converting this kinetic energy into electrical power. The amount of energy produced is contingent on several factors, including the wind speed, turbine size, and blade length. Essentially, larger wind turbines yield more energy [40]. As indicated by Reference [42], countries with the most extensive wind energy generation capacities include China (221 GW, boasting the largest onshore wind farm), the U.S. (96.4 GW, with the top 10 onshore wind farms), Germany (59.3 GW, leading in the installed wind power capacity in Europe), Spain (23 GW, covering 18% of its electricity supply), the U.K. (20.7 GW, home to the world's top

10 highest-capacity offshore wind projects), France (15.3 GW), Canada (12.8 GW), and Italy (10 GW) [43].

Wind energy has the potential to complement all other conventional and renewable energy sources in Nigeria, ensuring a stable supply of electricity. Its applications extend to irrigation and meeting domestic needs in rural regions. Historical records, as mentioned in Reference [44], trace the utilization of wind energy to propel boats along the Nile River as far back as 5000 BCE [45]. It is worth noting, as suggested in [46], that wind energy can not only power rural communities but can also help curb rural-to-urban migration. Furthermore, wind energy in Nigeria is advantageous due to its environmental friendliness, sustainability, and widespread availability. Given the rising costs associated with power generation, wind energy can serve as a supplementary source of electricity in the country. To effectively harness wind energy, key factors include the wind consistency, speed, density, and distribution and the suitability of locations for wind turbine installations [43].

Nigeria has yet to tap into the full potential of wind energy, as highlighted in Reference [47]. Notably, North African countries like Morocco, Egypt, and Tunisia have taken the lead in wind energy utilization. To unlock the complete spectrum of wind energy benefits, both onshore and offshore wind resources need to be explored. The distinction between onshore and offshore wind hinges on the wind's direction: onshore wind travels from the sea to the land, while offshore wind flows from the land to the sea. In the southern regions of Nigeria, wind speeds tend to be generally low, with some exceptions in coastal areas, as mentioned in [48]. Conversely, northern Nigeria boasts stronger winds, particularly in hilly terrains, as revealed in [49]. Africa has seen the completion of several wind energy projects, with others currently underway. However, the development of wind power on the continent has primarily centered on onshore projects, owing to a limited understanding of the potential for offshore wind energy. Figure 5 illustrates the wind speed distribution in Nigeria.

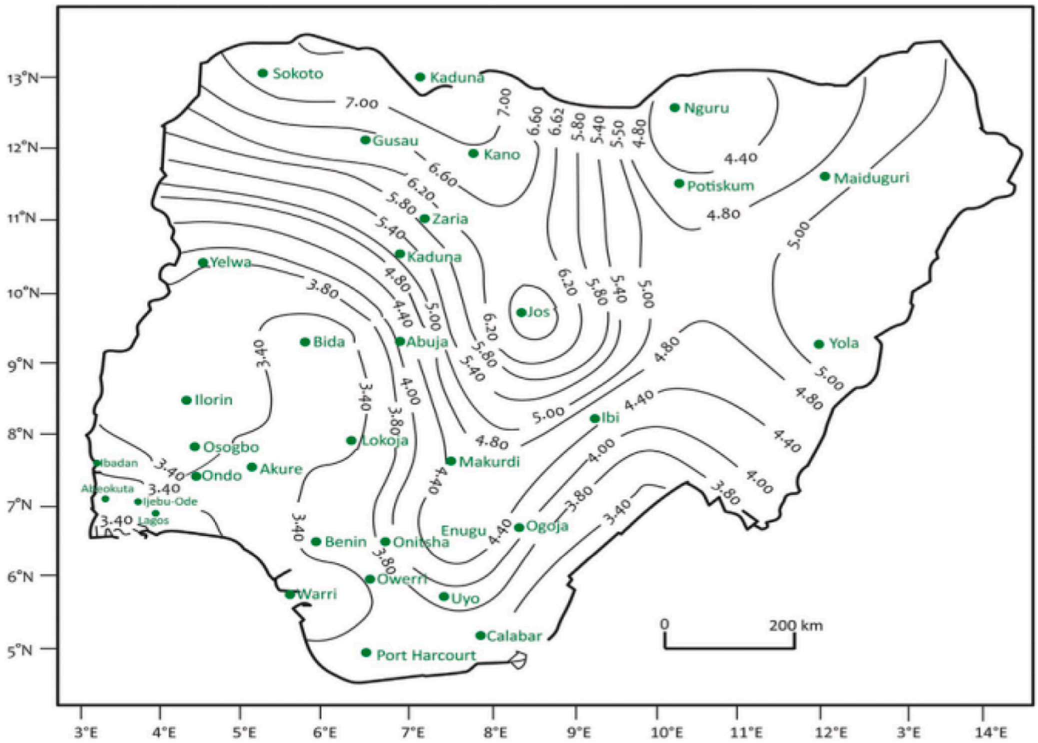

Figure 5. Wind speed distribution in Nigeria [43].

Olayinka [50] investigated the wind energy potentials of six high-altitude regions in Nigeria using Weibull distribution models and 36 years of wind speed data. The mean wind speed in Katsina was 9839 m per second, while the mean wind speed in Kaduna was 3397 m per second. In contrast to Gusau, which might be used for wind energy with taller turbine towers, Katsina and Kano are suitable locations for the construction of wind turbines. Kaduna, Bauchi, and Potiskum, however, have just a little amount of wind energy potential. Kano and Potiskum had the highest and lowest wind power density and energy, at 368.92 W/m^2 and 3224.45 kWh/m^2/year, respectively. Similarly, Adaramola and Oyewola [51] analyzed the distribution of the wind speed and the potential for wind energy at three locations in Nigeria's Oyo state using wind speed data that was gathered over a 12–20-year period. The average monthly wind speed in Oyo is 3.15 m/s, with power densities ranging from 27.08 to 164.48 w/m^2. For its 250 kilowatt maximum output and a minimum wind speed of 2.7 m per second, the WES30 wind turbine is universally recommended. In all except the windiest environments, low-rated wind turbines (those with a cut-in wind speeds of roughly 2.5 m/s) will produce the most energy. The G-3120 type with a rated wind speed of 8 m/s is recommended since it has a high-capacity factor. By modifying the specified wind turbine types to run at lower wind speeds than their rated wind speeds, the annual energy production and capacity factor may be greatly increased. R.O. Fagbenle [52] assessed the viability of wind power in the towns of Maiduguri and Potiskum in northeastern Nigeria by evaluating 21 years of average monthly wind speeds. Weibull distribution models with two parameters and other statistical methods were used to assess the data. The findings showed that both locations have the ability to generate independent, medium-scale wind energy. It was found that Maiduguri has a higher potential for wind energy than Potiskum. Compared to the dry season, the rainy season gives a better opportunity to capture wind energy. The most fruitful period of the year for wind energy harvesting in these areas may be between January and June.

Ubong et al. [53] conducted a more thorough study, using six methods to estimate the Weibull parameters and 10 years' worth of data on the typical daily wind speed from thirteen cities in Central and Southern Nigeria. The analysis's objectives were to learn more about the characteristics of the wind, how it varied, how much power it might provide, and how effectively estimating techniques are performed. The findings demonstrate that the wind speeds vary depending on the location, altitude, and season. Cities in the area fall under wind power classifications 1–4. The biggest wind-power-generating potential is in Obudu, and the most consistent wind is in Gboko. The maximum likelihood approach is the most effective strategy to estimate Weibull parameters. The report recommends that Obudu should have a reasonably strong wind turbine installed. Ayodele et al. [54] used data from daily average wind speeds gathered over a number of years to study the potential of wind energy for power generation across 15 distinct areas in Nigeria. The research assesses the potential for wind energy and finds viable methods for grid integration. Both S2 (Jos) and S3 (Kano), which have tremendous wind resources, are the most commercially feasible locations. The study's findings offer vital information on the potential of Nigeria's various zones for wind power and economic feasibility, which might aid in the development of wind power as part of a renewable energy policy. The author also considered the advantages of putting in place an off-grid wind energy conversion system to deliver water to three regions in Nigeria's Oyo state [55]. The analysis demonstrates that the wind power potential of the sites is adequate to fulfill the water demands of the areas using data from the Nigeria Meteorological Agency and water usage information. The project's best options are judged to be the Polaris P50 wind turbine and 320 L series Goulds submersible pumps. The system's annualized life cycle cost and unit cubic cost of pumped water were also calculated. Investors, decision-makers, and government representatives looking to solve water poverty in Nigerian communities will benefit greatly from the findings. One of the main issues with growing wind power in underdeveloped nations has been the lack of scientific data. The study by Ayodele et al. [56] provides information based on a thorough evaluation of the wind resource that takes into account environmental, social, and economic considerations. The information can be used by government officials, engineers, and others to determine the ideal locations for wind farms in Nigeria. For the developers of wind farms in Nigeria, this would result in the optimum investment and return on investment.

The technical and financial viability of two commercial wind turbines, the AN-Bonus 300 kW/33 and AN-Bonus 1 MW/54, in six high-altitude sites in Nigeria, was evaluated in different research by Olayinka et al. [57]. The capacity factors, annual power, and energy outputs, and economic evaluations of the wind energy conversion systems, were computed using the present-value cost approach. The most cost-effective sites for both wind turbine types were Kano and Katsina, where the AN Bonus 1 MW had an average minimum cost per kWh of USD 0.0222. The study also showed that for unrelated electrical and mechanical applications, Gusau and Kaduna were more profitable than diesel generators. In six districts of North Central Nigeria in 2012, Adaramola et al. [58] studied the potential for wind energy and the economic viability of using wind turbines. Wind speed data spanning 19 to 37 years were used to examine the performances of small- to medium-sized wind turbines. Based on levelized-cost economic research, it was established that the cost of energy production per kWh ranged from 4.02 to 166.79. The most and least suitable locations among those examined were Minna and Bida, respectively. The operational and maintenance escalation rate was raised from 0% to 10%, which resulted in an increase in the unit energy cost of 7%. The cost of energy was cut by 29% when the inflation escalation rate was raised from 0% to 5%, but the return on investment fell from 11.54% to 6.25%. Minna had the strongest potential for wind energy development based on the energy output and capacity factor. In addition, Effiom et al. [59] carried out research to evaluate the economic cost of constructing a 500 MW offshore wind turbine (OWT) farm in Nigeria using a created model. According to the study, the operating costs (OPEX) make up less than half of the project costs, while capital expenses (CAPEX) account for more than half (OPEX). The price of essential OWT components makes up around 55% of the total cost. Furthermore, the model predicts a decrease in the levelized cost of electricity (LCOE), with the exception of operations and maintenance (O&M), for all project phases, with a maximum decrease of 4.95 percent for a 4 MW power rating. The findings indicate that Nigeria has the capacity to expand OWT farms, and the model is suitable for underlying OWT research.

The impact of integrating a sizable Doubly Fed Induction Generator (DFIG)-based wind energy conversion system (WECS) into Nigeria's 52-bus, 330 kV power grid was also examined by Bukola Babatunde [60]. The research calculates the maximum active power margin (APM), minimum reactive power margin (RPM), and critical voltage–reactive power ratio (CVQR) of the system buses using PV and QV curve analysis. The optimum option to maintain bus voltages at the appropriate level, eliminate concerns about overvoltage in the northern area, and still satisfy energy demands, according to the simulations, is a 35% DFIG-based WECS penetration level. This study demonstrates that a large-scale DFIG-based WECS is a potential method for increasing the voltage stability and supplying energy. Also, Julian C. Aririguzo [61] used a two-parameter Weibull distribution model to assess the viability of wind energy in Umudike (Umuahia). The findings point to the viability of wind energy in Umudike for the proposed system; the next step is to design and build wind turbine blades that are tailored to the local wind conditions. To efficiently manage energy generation and provide power to isolated people without basic amenities, the mechanics of wind turbines will be coupled with computing and control skills. The project has great potential to produce power with few negative environmental consequences for the host communities. For the Nigerian village of Giri, Sani Salisu [62] also assessed the viability of creating a hybrid renewable energy system using solar and wind power. This study assessed the techno-economic and environmental aspects of the project using the simulation tool called the hybrid optimization model for electric renewables (HOMER). According to the research, the PV/diesel/battery combination is the best option for supplying power to Giri village. With a COE of 0.110 USD/kW, an NPC of USD 1.01 million, a renewable proportion of 98.3%, and GHG emissions of just 2889.36 kg per year, this arrangement has the lowest COE. According to the research, the hybrid PV/diesel/battery system used to generate electricity in the Gwagwalada community is both environmentally and financially sound. The study offers conclusions that are relevant to other developing countries where most rural populations do not have access to the grid (2019).

Ubong et al. [53] analyzed ten years of daily wind speed data from thirteen cities in Central and Southern Nigeria using six methods to estimate the Weibull parameters. It aimed to assess the wind characteristics, variation patterns, and wind power potential. Results showed significant variation in the wind speeds, with Obudu recording the highest speeds and power densities, and Afikpo the lowest. The study found that the wind speeds vary by location, elevation, and season, and it recommended wind turbine installations at higher elevation areas like Obudu. Among the estimation methods, the maximum likelihood method proved the most accurate, while the graphical method was the least effective. Ezekwem et al. [63] focused on rural electrification in Choba, Port Harcourt, Nigeria, exploring the integration of renewable energy systems for enhanced electricity access. Initially, it assessed Choba's current electrification status, and it then used HOMER pro software to evaluate the optimal mix of photovoltaic modules and wind turbines. The community's normal energy demand was estimated at 39.12–46.80 MW. In 2021, the Port Harcourt Electricity Distribution Company supplied 6067.64 MWh. The study proposes an on-grid hybrid system combining photovoltaic modules and wind turbines, achieving an optimal net present cost of USD 20.8 million and a levelized cost of energy of 0.0117 USD/kWh. This configuration significantly reduced energy costs by about 87% compared to non-MD customers in Band D, highlighting its efficiency and cost-effectiveness in addressing Choba's power outages.

Babatunde et al. [64] investigated the potential of integrating hydrogen storage systems in household renewable energy systems in sub-Saharan Africa, focusing on solar photovoltaic (PV) power, micro-wind turbines, and fuel cells. Using the HOMER software, it analyzed seven solar PV tracking orientations in South Africa and Nigeria. The optimal system for Nigeria, involving PV power, fuel cells, electrolyzers, batteries, and hydrogen storage, operated best in a daily adjusted horizontal axis mode, costing USD 9421, with an energy cost of 0.754 USD/kWh. For South Africa, a similar system in dual-axis mode cost USD 8771, with an energy cost of 0.701 USD/kWh. The study concluded that adding hydrogen storage is technically viable for most sun-tracking configurations in both locations, and its economic viability could improve with lower hydrogen subsystem costs. Adetunla et al. [65]'s research focused on addressing energy deficits in developing nations by designing and fabricating a small-scale horizontal axis wind turbine (HAWT) using locally sourced materials like wood, PVC, acrylic glass, Teflon, and steel. The project aimed to create a hybrid solar–wind power system for irrigation. The wind turbine's power output was measured at 40 W, 41 W, and 43 W for wind speeds of 5, 10, and 15 m/s, respectively. Notably, it performed best at a low speed of 5 m/s, with an R2 value of 0.9602. This wind turbine was integrated with a 40 W solar tracking system to form a more stable power supply for soil monitoring and irrigation, demonstrating a cost-effective, sustainable alternative for smart solar panel irrigation systems.

Babatunde et al. [66] utilized Criteria-COPRAS tools to evaluate renewable energy systems for residential use in Lagos, Nigeria, encompassing wind turbines, solar PV power, fuel cells, electrolyzers, hydrogen storage, and batteries. Economically, the most optimal solution was a solar PV and battery system, with a total net present cost (TNPC) of USD 9060 and an initial investment of USD 3818. However, when considering multiple criteria (economic, technical, environmental), a hybrid system combining solar PV power, fuel cells, wind turbines, and batteries emerged as superior, featuring a TNPC of USD 10,324 and an initial cost of USD 7670. The research highlighted the importance of multi-criteria evaluation for effectively integrating hydrogen storage into hybrid energy systems [67,68].

Based on the comprehensive review of various studies, promoting sustainable wind energy in Nigeria requires a complex approach. First, investment in research and development is crucial to optimize wind turbine designs for local conditions, as demonstrated by Adetunla et al. [65] in fabricating a small-scale horizontal axis wind turbine using locally sourced materials. Emphasizing the development of low-speed wind turbines, as was shown to be effective in the study, can enhance energy production in regions with lower wind speeds. Additionally, integrating wind energy into hybrid systems, as seen in the works of Ezekwem et al. [63] and Babatunde et al. [66], can increase reliability and efficiency, thereby making wind energy more attractive. Encouraging public–private partnerships for the development and installation of these systems can accelerate this integration. Moreover, expanding the infrastructure for wind energy in high-potential areas, such as Kano and Obudu as identified by Ubong et al. [53], is essential. This includes building better access roads and transmission lines to remote wind farms. Education and awareness campaigns are also vital to increase the public acceptance of and support for wind energy projects. Lastly, policy incentives and subsidies from the government could lower the initial investment costs, making wind energy projects more financially feasible. This approach, coupled with improved economic metrics like reduced levelized costs of energy, as shown in various studies, can make wind energy a more attractive option for investors and stakeholders. By implementing these strategies, Nigeria can effectively harness its wind energy potential, contributing to a more sustainable and self-sufficient energy future.

2.3. Hydropower Energy Potential in Nigeria

Hydropower stands as a cornerstone of the global renewable energy portfolio, boasting an impressive total installed capacity of approximately 1360 GW according to the International Hydropower Association (IHA) 2022 hydropower status report, with the 34 GW additional capacity in 2022 providing more than 15% of the world's electricity [69,70]. This renewable energy source, found at various scales, has played a vital role in meeting the world's growing electricity demands while significantly reducing greenhouse gas emissions. Leading the pack, countries like China, who has been contributing a higher percentage since 1991 with its established, extensive large-scale hydropower infrastructure, contributing substantially to its energy grids, contributed about 24 GW of hydropower in 2022 out of a global installed capacity of 34 GW (for 2022) [69–71]. Africa is the second region with the largest exploitable hydropower potential after East Asia and the Pacific region, with a capacity of 630 GW [70]. However, about 5.9% of this total has been exploited. This shows that Africa is far behind and contributes a small percentage of hydropower potential to the global electricity based on the installed capacity. Figure 6 shows the world's exploitable hydropower, installed capacity, and untapped hydropower by each region obtained from data published by the IHA 2023 World Hydropower Outlook [70].

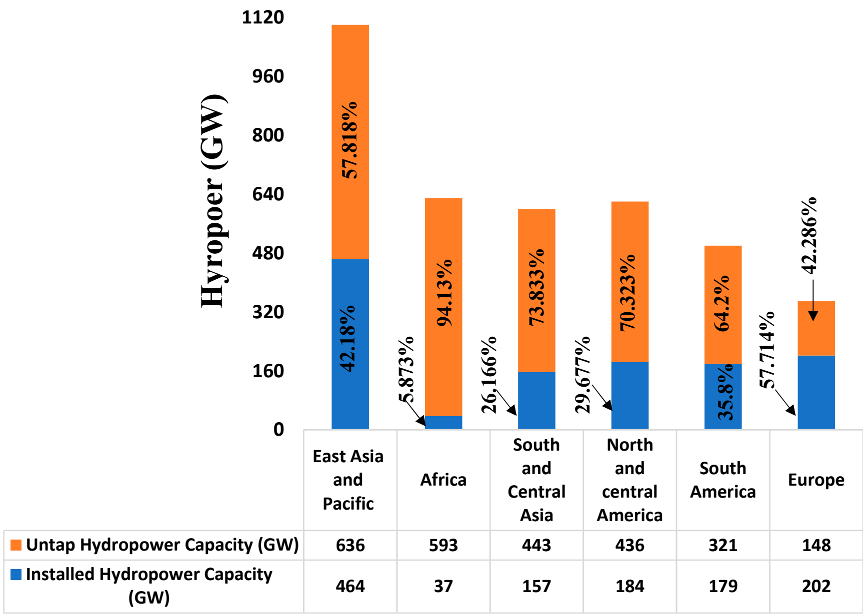

Figure 6. Comparison of the total installed and untapped global hydropower by region.

Nigeria is one of the African countries endowed with abundant water resources, which boasts significant hydropower plant potential and could help the nation to curtail the electric power problem, yet little of this power has been utilized [72]. Though there is no specific standard for the classification of hydropower but given the fact that Nigeria is blessed with different water bodies from large-sized streams, Nigeria's hydropower is classified based on the size and facility of its power plants [21,72]. Table 1 presents the classes of Nigeria's hydropower ranges, from Pico to large hydropower [21,72–76].

Table 1. Classification of hydropower.

Different Types of Hydropower	Capacity
Pico hydropower	$\leq$5 kW
Micro hydropower	$\geq$5 kW and $\leq$100 kW
Mini hydropower	$\geq$100 kW and $\leq$1 MW
Small hydropower	$\geq$1 MW and $\leq$10 MW
Medium hydropower	$\geq$10 MW and $\leq$100 MW
Large hydropower	>100 MW

Nigeria has the capacity to generate around 86,400 GWh of electricity annually from its large-scale hydropower, with an exploitable capacity of 24 GW. However, about 14,750 MW of the total has been identified, while the total installed capacity stands below 2400 MW as of 2022, representing about 16% of its identified potential, highlighting the vast untapped potential in the country [20,73,77–82]. Notable among the large hydropower plants in Nigeria are the Kainji, Jebba, and Shiroro hydropower stations, with installed capacities of 760 MW, 570 MW, and 600 MW, respectively, and representing 30% of the national electricity [20,78,79,83–86]. These three stations are strategically located on the Niger and Kaduna rivers. Nigeria's dedication to harnessing its hydropower potential to meet its growing energy demands, reduce reliance on fossil fuels, and enhance energy security while contributing to the global transition toward renewable energy sources has brought about the Zungeru Hydroelectric Power Plant, which is currently under construction and is projected to add 700 MW to the national grid. As part of its commitment to sustainable energy development, Nigeria is embarking on ambitious future expansion plans, including the Mambilla Hydroelectric Power Project, with the potential to contribute up to 3050 MW [73,74]. Nigeria's small hydropower sector also represents a crucial facet of the nation's journey toward sustainable and equitable energy access. SHP technologies are cost-effective, scalable, reliable, and environmentally friendly, and they require minor maintenance and can work over a long time. These small hydropower sites, scattered predominantly in rural and off-grid areas across the country with 278 identified exploitable sites, exists with a potential capacity of 734.2 MW from the estimated potential of 3500 MW [20,21,73,77,80,83,87–90]. Boasting diverse capacities, only a 59.2.0 MW capacity is installed, as shown in Table 2, but these capacities collectively contribute to Nigeria's considerable untapped hydropower potential [21,72,77,83,84,87]. Table 2 shows the information related to the installed small hydropower stations in Nigeria.

Table 2. Small hydropower stations in Nigeria.

Rivers	Location (State)	Installed Capacity (MW)
Annoke Ugbokpo	Benue	1.2
Bagel I	Plateau	1
Bagel II	Plateau	2
Bakalori	Sokoto	3
Challawa Gorge	Kano	7
Ikere	Oyo	6
Kurra	Plateau	8
Kwali Falls	Plateau	6
Lere	Plateau	8
Ouree	Plateau	2
Oyan	Ogun	9
Tiga	Kano	6
Total		59.2

Harnessing this energy to its fullest would be instrumental in narrowing the energy divide, particularly in remote communities of the country. Figure 7 shows the relationship between the exploitable hydropower in Nigeria and the installed capacity for both large- and small-scale hydropower.

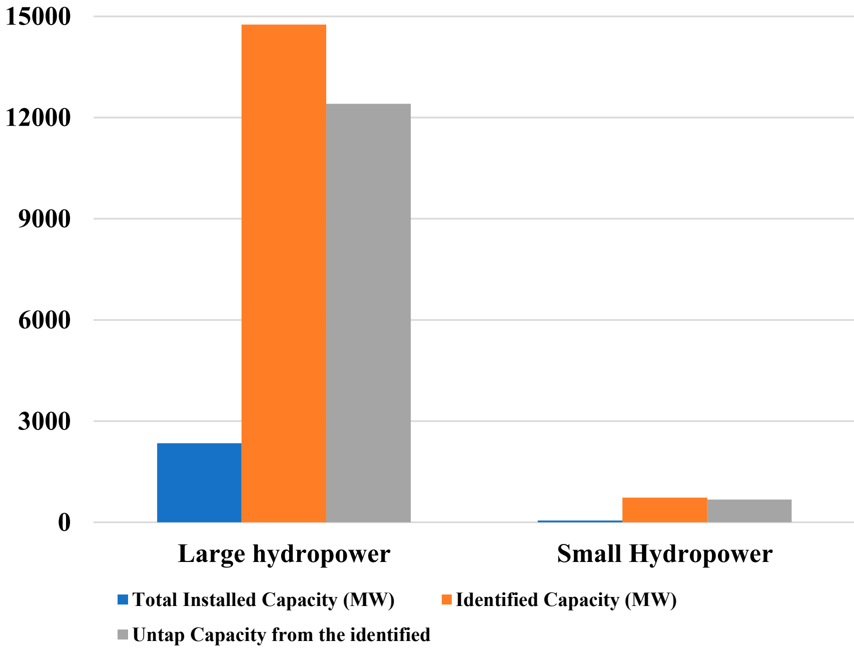

Figure 7. Comparison of Nigeria's hydropower: identified, total installed, and untapped capacities identified for both large and small hydropower.

To further promote the Small Hydropower River Basin Development, the Authorities (RBDAs) Act of 1979 mandated the provision of a domestic water supply, the development of irrigation facilities, improved water navigation, and hydroelectric power generation [72]. Since then, much research has been conducted to exploit small hydropower resources, which are available within the river basins, to incorporate them into the existing one.

Fasipe et al. [21] evaluated the small hydropower (SHP) potentials of 148 points in the Osse Sub-Basin (OSB) in Nigeria using spatial technology and hydrological modeling and identified promising SHP project sites that can earn certified emission reduction (CER) credits. This study proposes the first clean development mechanism (CDM) approach in Nigeria by identifying viable SHP project locations that might generate marketable CER credits, and it offers the reliable hydrological data and template needed to assess the SHP potentials of rivers in river basins with little data. The OBS was characterized using remote sensing (RS) and geographic information system (GIS) tools, and the stream peak discharge was estimated using the Natural Resources Conservation Service—Curve Number (NRCS-CN) model. This model was able to identify 18 points with potentials of energy generation between 677.485 kW and 7622.877 kW, with an annual flow surpassing 92%. To facilitate the future activation of SHP resources, the discharge, potential power, recommended turbine, and cost implication to erect each of the 18 points were evaluated [21].

Oyinna et al. [80] analyzed the potential for small hydropower projects in Nigeria using geographic information system software. The author evaluated water areas and waterline data overlaid in the six geopolitical zones of Nigeria to identify potential hydropower sites. The potentials of the different states were examined based on data for inland waters and areas subject to flooding extracted from ArcGIS. Statistical analyses were conducted to evaluate the SHP potentials in the different zones. Interpolations using Inverse Distance Weighting identified suitable areas for dam schemes. The analysis reveals significant SHP potentials across various Nigerian states. States like Yobe have many potential sites for small dams and inland water sites for large dams. Other suitable states identified include Kebbi, Niger, Edo, Anambra, and Jigawa. The reiterate issues like limited data availability, lack of expertise, and inadequate regulations pose challenges to hydropower site assessment in Nigeria using ArcGIS. The study's results can aid Nigeria's energy planning and expansion of access to remote areas by the better utilization of the hydropower potentials identified across the states.

Okedu et al. [91] investigated the potential of harnessing small hydropower (SHP) in Cross River state, Nigeria. The author analyzed the potential SHP sites in the hills and forest cover region and set the criteria for ranking the sites according to the potential power and cost. The study was based on the float measurement mathematical model to measure the river discharge for both the lean and peak seasons. The cost of the SHP project was initially based on the power potential of the flow in the lean season, but the actual cost was established based on the extracted peak seasonal power, indicating the influence of power potential variation on project costs. The potential power and the cost of 20 SHP sites were investigated for both the lean and peak seasons. It was revealed that Kundeve/Stone Market–Obanliku have the highest power potential of 13.13 MW for the peak season, despite the average lean season head and flow of 50 m and 0.8237 m^3/s, respectively (Figure 4). Two other locations were also identified as potential sites for hydropower energy harvest in the state. The study also emphasizes the concentration of hydropower technology compared to other forms of renewable energy sources, the potential use of available hydropower to meet the electricity needs of isolated communities, the site-specific nature of hydropower schemes, and the influence of environmental factors on the power output. Nchege et al. [92] investigated the impact of hydroelectric power production and energy consumption on Nigeria's economy using an Auto-Regressive Distributed Lag (ARDL) model. The analysis found that hydroelectric power generation has a significant positive effect on Nigeria's Gross Domestic Product (GDP) in both the short and long term. The study suggests that the underutilization of Nigeria's abundant hydroelectric resources is a contributing factor to this adverse economic impact. The paper recommends that the Nigerian government support hydroelectric companies, provide favorable environments for investors, and form partnerships to harness these resources. The study's findings highlight the importance of policy formulation and effective implementation to ensure sustainable hydroelectric power development and economic growth in Nigeria.

Fakehinde et al. [93] examined the relationship between hydroelectric power generation (HEPG), economic growth (EG), and financial development (FD) in the world's leading hydroelectric energy-generating countries from 1990 to 2020. Employing second-generation panel data analysis methods, the study found that HEPG positively impacted both EG and FD, with bilateral causality observed between HEPG, EG, and FD. The findings supported the feedback hypothesis, highlighting HEPG as a significant driver for EG and FD. The study recommended increasing the number of hydroelectric power plants and providing policy support for sustainable development while also emphasizing the importance of environmentally friendly technologies. Additionally, it called for further research into the relationship between HEPG and FD, ecological footprints, and renewable energy mixes. Pavanelli et al. [94] examined the evolution of Nigeria's electricity industry using the Meta-Institutional Development and Analysis (MIDA) framework, analyzing pivotal agents' endowments and their influence on the choice of energy sources, technology, and governance. The study identified two key transitions in electricity generation sources: from coal to hydropower and from hydropower to gas, alongside shifts in political governance from colonial to military rule and, later, to privatized and hybrid governance. The dominance of military elites and federal government over Nigeria's electricity industry has led to a ten-fold increase in the natural gas-generated capacity since 1980. The study highlights the effectiveness of the MIDA framework in revealing institutional preferences and power dynamics, recommending its use to understand and clarify power disputes and biophysical conditions influencing the country's electricity industry. Further research is suggested to explore these institutional dynamics in more detail, providing assessments of success or failure for various energy sources and governance options.

2.4. Solar Energy Potential in Nigeria

Solar energy, derived from the sun's radiant light and heat, is increasingly being recognized as a vital component of the global energy landscape [95]. The sun, which has illuminated Earth for approximately 4.5 billion years, offers an almost inexhaustible source of energy, vastly surpassing humanity's total energy demand. Solar cells, primarily made from silicon—the second most abundant element in the earth's crust—efficiently transform solar energy into usable electricity. These solar technologies not only offer a sustainable solution to meet energy needs but are also economically viable due to their low operational costs [96,97]. The global shift towards solar energy is underscored by its minimal spatial requirements for installation and its compatibility with various renewable energy forms. This versatility allows solar energy to provide heat, electrical, kinetic, and chemical energies, enhancing its integration into different energy systems. The widespread adoption of solar energy, particularly through photovoltaics, presents a significant opportunity for energy-strapped regions like Nigeria, where it can propel progress towards Sustainable Development Goal 7 (SDG-7) by ensuring clean, affordable, and reliable energy for all [95]. Despite its high initial costs, the potential for solar energy in Nigeria is bolstered by the country's geographical position near the equator, promising abundant sunlight year-round and a substantial contribution to reducing energy poverty and supporting sustainable development [96,98].

Nigeria has immense solar energy potential due to its favorable geographical location near the equator, which provides abundant sunshine throughout the year [99]. The country's solar energy potential is estimated at around 6500 terawatt hours (TWh) per year, which is currently higher than the country's current electricity output at an average of 3570 TWh [100]. This potential is further supported by Nigeria's wind potential, approximately at 76 gigawatts, indicating that there is an abundant resource available for renewable energy generation in the country [100]. Research indicates that solar energy has the significant potential to contribute to Nigeria's energy mix, providing clean, reliable, and stable power to its population [95]. The country's solar radiation varies from 3.5 to 7.0 kWh/m^2 per day, with an average solar radiation level of about 5.5 kWh/m^2 per day [96]. The estimated potential of solar energy in Nigeria, considering a 5% device conversion efficiency, is 5.0×10^{14} KJ of useful energy annually, equivalent to about 258.62 million barrels of oil produced annually and about 4.2×10^5 GWh of electricity production in the country. Despite the vast potential, solar energy adoption in Nigeria faces several challenges, including insufficient local production, low efficiency, and inadequate infrastructure.

Extensive research has been conducted to assess the solar energy landscape, focusing on critical factors such as irradiation and radiation intensity. Banisile et al. [101] conducted a comprehensive analysis that revealed the greater solar irradiation in the northern regions compared to the south, reinforcing the suitability of these areas for solar power generation, as depicted in Figure 8. A separate study conducted by Bawonda et al. [102] estimated the solar energy potential of Nigeria through analytical and simulation techniques, considering the techno-economic and environmental aspects of renewable energy projects. Their findings emphasized Sokoto as an ideal location for solar energy investment, boasting abundant solar energy output and an attractive internal rate of return. These findings were further supported by Adekunle [103] and Ohunakin et al. [104], who highlighted the prevalence of elevated solar radiation in the northern parts of Nigeria, reaffirming the region's suitability for solar power projects. In line with this, the northern regions of Nigeria, particularly the northeast and cities like Kano [105], Sokoto [95], and Niger State, have the highest solar energy potentials due to their higher levels of solar radiation compared to the other regions of the country.

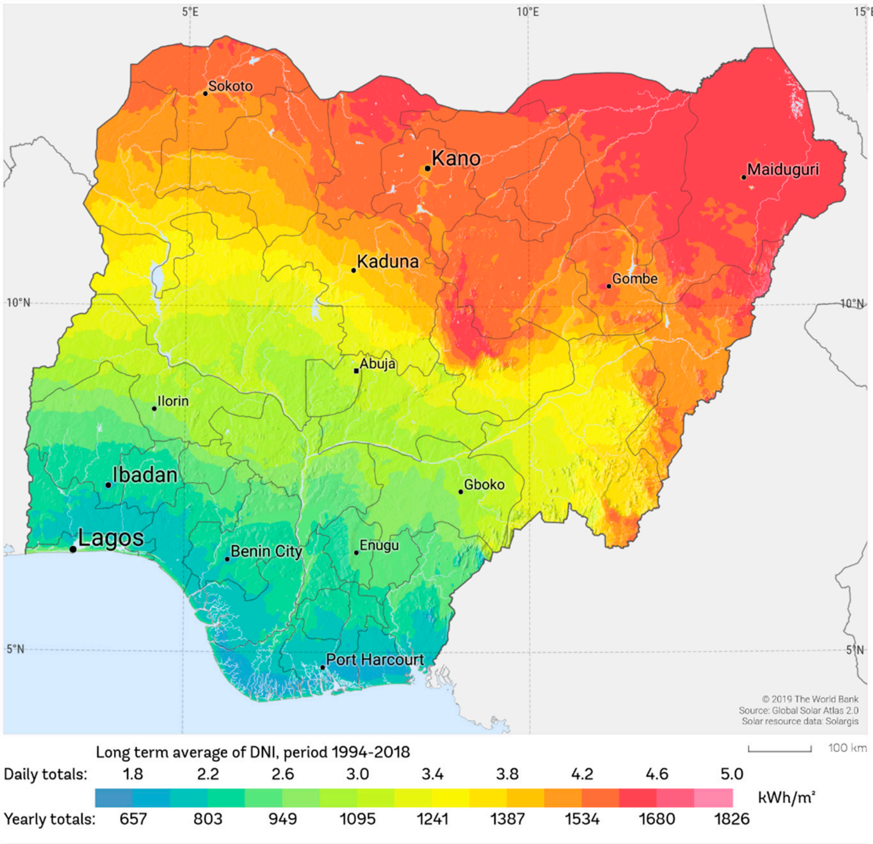

Figure 8. Illustration of geographical location and solar radiation distribution [106].

Recent studies have focused on evaluating the performance, economic viability, and sustainability of solar photovoltaic (PV) systems across various applications and regions in Nigeria. Diyoke et al. [107] analyzed grid-connected PV systems in Enugu, Nigeria, and highlighted their economic feasibility and performance based on 10 years of solar radiation data. Their findings demonstrated that a 1 kW grid-connected system could generate an average of 4.5 kWh/day, with a capacity factor of 18.8%. Ohunakin et al. [108] assessed PV technologies across multiple locations, emphasizing the high-energy-yield potential of monocrystalline silicon modules, ranging from 1400 kWh/kWp in the south to 1800 kWh/kWp in the north annually. Additionally, Hillary [109] investigated the techno-economic sustainability of a solar/battery/diesel hybrid mini-grid, showcasing positive environmental impacts, including a Net Present Value (NPV) that indicated financial feasibility, a substantial 92.9% reduction in greenhouse gas (GHG) emissions, a 4-year payback period, and an annual electricity export of 203 MWh.

Zarmai et al. [110] conducted a techno-economic evaluation of a hybrid mini-grid system for an academic institution in Kaduna, Nigeria, demonstrating the technical and economic viability of the hybrid system, with a net present cost (NPC) of USD 182,065.20, a levelized cost of energy (LCOE) of 0.00198 USD/kWh, and a renewable fraction (RF) of 98.3%. Moreover, Emezirinwune et al. [111] explored the integration of hybrid renewable energy systems (HRESs) in Nigeria's agricultural sector, highlighting the advantages of solar PVs and its potential for carbon emission reduction and additional income generation. The study by Owolabi et al. [112] evaluated the performances of different grid-connected PV systems and provide valuable insights for system selection. The findings highlight the amorphous silicon (asi) systems with the highest energy output and performance ratios, while the monocrystalline silicon (msi) systems exhibit the highest efficiencies with the lowest overall losses. Finally, Amole et al. [113] conducted a comparative analysis of control strategies for a solar PV/diesel generator system in remote Nigerian communities. Their study considered technical, economic, and environmental factors and identified the PV-DG-

LF configuration as optimal. This configuration achieved an impressive 80.7% renewable penetration, minimal fuel consumption (6594 L), and low CO_2 emissions, aligning with Sustainable Development Goal (SDG) 7 in providing affordable, clean, and reliable energy access. These studies provide comprehensive insights into the performance, economic viability, and sustainability of solar energy systems in Nigeria, highlighting how solar power can propel Nigeria towards a more sustainable and resilient energy future.

3. Challenges Associated with Slow Adoption of RE in Nigeria

The development of renewable energy (RE) technologies in Nigeria has been slow, despite acknowledging their potential as a sustainable alternative to fossil fuels. Investment in RE lags significantly behind funds directed towards conventional power development. Moreover, the implementation of established policies and targets has fallen short of expectations. To achieve widespread RE development in Nigeria, it is crucial to address the challenges arising from ineffective policies, insufficient training, high costs, and a dearth of skilled personnel. These challenges are summarized in Table 3.

Table 3. Summary of the challenges for the adoption of RE in Nigeria.

RE Source	Technical Potential	Current Status	Challenges	Drivers	References
Solar Energy	The overall technical potential for solar PV is vast, with projections ranging up to 427 GW of the installed capacity.	Adoption of solar energy remains low despite significant potential. Solar home systems and mini-grids are growing, but large-scale solar plants are still in their infancy.	– High upfront costs for solar PV; – Lack of financing models for rural and urban adoption; – Policy inconsistency and lack of incentives.	– Declining cost of solar PV technologies; – Favorable geographic conditions; – Growing off-grid electrification demand.	[114–116]
Wind Energy	Estimated wind energy potential of 2–4 m/s at a 10 m height. Suitable areas for wind energy are largely in the northern regions. Total technical potential for onshore wind power is about 27 GW.	Wind energy adoption is minimal, with only a few pilot projects in states like Katsina. Large-scale wind farms have not been established.	– Low wind speeds in most regions; – Lack of technical expertise; – Inadequate investment in wind technology.	– Wind potential in Northern Nigeria (e.g., Sokoto, Kano, Borno); – Rising demand for decentralized energy solutions.	[117,118]
Hydropower	Estimated potential of 14,120 MW (small, medium, and large hydropower). Small hydropower potential alone is about 3500 MW.	Hydropower is the most developed RE source, contributing about 30% of Nigeria's energy mix, mainly from large dams such as Kainji, Shiroro, and Jebba. Small hydropower remains underdeveloped.	– High initial capital costs for dam construction – Environmental and social impacts, including displacement; – Poor infrastructure for rural communities.	– Strong government focus on hydropower; – Development of small hydropower to boost rural electrification; – Renewable energy policies (e.g., the Renewable Energy Master Plan).	[119–121]
Biomass Energy	The biomass potential in Nigeria is vast, with estimates ranging from 144 million tons/year from wood to over 14.6 million tons/year from crop residue. The biomass-to-electricity potential is about 5 GW.	Biomass use for traditional cooking (wood, charcoal) and modern cooking (biogas) is widespread. However, modern biomass for electricity remains limited due to the lack of technology and industrial interest.	– Lack of infrastructure for modern biomass technologies; – Deforestation and unsustainable harvesting practices; – Lack of awareness and policy focus.	– Abundance of agricultural waste and wood biomass; – High demand for rural electrification solutions.	[122,123]

One primary challenge lies in ineffective policies. Although the Energy Commission of Nigeria (ECN) has introduced several policies on energy generation and utilization, the outcomes have been limited, resulting in near-zero RE penetration. Subsidies for grid electricity and incentives for conventional generation discourage investments in RE, while regulatory risks and the lack of guaranteed grid access for decentralized renewable electricity deter investors and financial institutions. Additionally, inadequate funding facilities pose a significant barrier. Financial institutions perceive RE investments as high-risk and prefer to lend for conventional power plants. This mindset, coupled with the perception that RE technologies such as solar, electric vehicles (EVs), and biofuel plants are not yet mature enough for significant investment, leads to higher interest rates and discourages long-term loans. Consequently, the high cost of RE technologies renders them unaffordable for many Nigerians and rural communities without financial support.

A significant challenge in Nigeria's renewable energy transition is the disparity between the required investment and the available funding. According to the International Renewable Energy Agency, Nigeria needs approximately USD 10 billion annually to achieve its renewable energy goals by 2030, which includes expanding its renewable energy capacity to 10 GW [124]. However, the current investment levels are far below this target. In sub-Saharan Africa, annual renewable energy investments averaged around USD 5 billion between 2010 and 2020, which is insufficient to meet the ambitious goals of countries like Nigeria [125].

For instance, projects like the Solar Power Naija Project, which aims to provide solar energy to 5 million households, have experienced delays due to funding shortages. Similarly, the Zungeru Hydropower Project, a key initiative to boost Nigeria's renewable energy capacity, has faced challenges in securing adequate financing, contributing to project delays [116,117]. Furthermore, compared to countries like Morocco, which has benefitted from substantial international funding for its solar projects, Nigeria struggles to attract similar levels of financial support. Morocco's ability to fast-track renewable energy infrastructure highlights the stark contrast in the funding availability across African nations [126].

Furthermore, a major obstacle to RE adoption in Nigeria is the lack of awareness among the population. With over 200 million people, 60% of whom reside in remote or rural areas with limited access to electricity, the penetration of RE technologies remains low. This lack of awareness contributes to a perception of RE investments as high-risk due to their low acceptance. Diesel and petrol generators continue to dominate power generation for homes and businesses, despite their high carbon emissions, primarily due to a limited understanding of the benefits offered by RE technologies. Enhancing information dissemination about applicable RE solutions could boost adoption rates and contribute to climate change mitigation efforts.

One of the major hurdles to Nigeria's renewable energy adoption is the significant infrastructural decay across its energy sector. Despite its rich endowment of oil, gas, and renewable resources, outdated power plants, an insufficient grid capacity, and poor maintenance continue to limit the country's ability to meet its electricity needs. For instance, the Egbin Power Station, one of the largest in Nigeria, has operated far below its capacity due to outdated equipment and poor maintenance practices [127]. Additionally, the national grid suffers from frequent failures due to underfunding and the inability to integrate new renewable energy sources into the grid efficiently [127]. Addressing these infrastructural deficiencies is crucial to achieving a more reliable and sustainable energy supply.

Another challenge stems from the high initial cost of RE technology deployment. This cost disparity is reflected in the energy produced, making RE appear more expensive compared to conventional electricity. Moreover, Nigeria's limited local production capacity for RE components worsens the situation. For instance, the manufacturing capacity for solar PV and small hydropower (SHP) components is minimal, and other RE systems have virtually no local production. This reliance on imports introduces additional supply chain constraints, such as extended project implementation cycles, high import tariffs, and cargo clearance bottlenecks, ultimately driving up costs. However, trends are shifting as international markets witness declining costs for RE components and more solar module production machines are being imported into Nigeria. A comparative analysis of renewable energy resources in Nigeria reveals key differences in their costs, operational efficiencies, and sustainability, helping to guide strategic investment decisions. Table 4 provides an overview of these factors.

Table 4. Comparative analysis of renewable energy resources in Nigeria.

Energy Resource	Cost per MW Installed (USD)	Operational Efficiency (Capacity Factor)	Grid Integration	Long-Term Sustainability	References
Solar	USD 1.3–2.5 million	18–24% (dependent on region)	Easy to integrate, ideal for off-grid systems.	High: abundant, low environmental impact.	[128,129]
Wind	USD 1.5–2.8 million	30–40% (higher in northern Nigeria)	Moderate, requires regional infrastructure improvements.	High: sustainable in windy regions.	[43,128]
Biomass	USD 2.5–4 million	50–85% (depending on feedstock availability)	Suitable for rural areas, but feedstock reliability is crucial.	High: helps waste management, carbon-neutral.	[43,130]
Hydropower	USD 2.5–5 million	40–90% (dependent on water flow)	Good for baseload power but limited by geography.	High: reliable but water-dependent.	[43,128,130]

This comparison highlights the distinct strengths and challenges of each renewable energy resource. Solar energy, with its relatively lower cost and easy off-grid integration, is ideal for rural electrification projects. Wind energy offers higher operational efficiency, particularly in northern regions with strong wind potential, but requires infrastructure improvements for grid integration. Biomass is highly efficient but dependent on reliable feedstock supplies, making it suitable for industrial and rural applications. Hydropower remains the most reliable source for baseload power, though its availability is limited by geography and water resources.

Corruption remains a deeply entrenched challenge in Nigeria's energy sector, often undermining efforts to enhance the infrastructure and renewable energy capacity. Following the 2013 privatization of the electricity sector, corrupt practices in procurement and contract awards have inflated costs and delayed the completion of key projects [127,129]. As a result, power generation companies (GenCos) and distribution companies (DisCos) operate inefficiently, exacerbating the nation's energy deficit. For example, mismanagement and corrupt practices during the procurement process have led to the installation of substandard equipment in several renewable energy projects, contributing to an unreliable power supply [125]. To address these issues, robust anti-corruption measures, such as transparent procurement processes and independent project monitoring, are essential to restoring confidence in the sector [127].

Lastly, the lack of sufficiently trained personnel poses a considerable challenge. Nigeria currently lacks the technical expertise required to effectively address its energy demand and supply challenges. Successful RE initiatives demand trained local technicians for maintenance and education purposes. The insufficient transfer of technical skills to recipients of RE technologies leads to inefficiencies, necessitating more training programs for Nigerians in relevant skill sets, especially in rural areas. This training would enable them to handle the routine maintenance of RE systems. While energy research centers and other institutions have made efforts to develop manpower for the RE sector, further measures are needed to address the existing skill gap.

4. Energy Policies in Nigeria

The Electric Power Implementation Committee (EPIC) laid the groundwork for the National Electric Power Policy (NEPP) in 2001 to reform Nigeria's power sector. This initiative proposed three key steps: privatizing the electricity sector and introducing Integrated Power Producers (IPPs); removing subsidies, increasing competition among market participants, and selling excess power to DisCos; and implementing efficient pricing for the power supply. The Energy Commission of Nigeria (ECN) developed the National Energy Policy (NEP) in 2003, which was later reviewed in 2006 and 2013, to promote energy security, diversify the energy mix to include more clean energy forms, and ensure affordable energy access to contribute to environmental conservation and sustainable development [126,127,131].

To further these goals, the National Planning Commission (NPC) introduced the National Economic Empowerment and Development Strategy (NEEDS) in 2004 to eradicate poverty by producing essential goods, privatizing government infrastructure to ensure quality service delivery, and encouraging clean energy by suggesting the creation of clean energy agencies. In 2006, the Federal Ministry of Power and Steel (FMPS) launched the Renewable Energy Policy Guide (REPG) to mandate 5% of Nigeria's electricity generation from renewables and a minimum generation of 5 TWh. In collaboration with the United Nations Development Program (UNDP), the ECN also developed the Renewable Energy Master Plan (REMP) in 2005 and reviewed it in 2012, emphasizing clean energy use in buildings, grids, and off-grid systems. The National Renewable Energy and Energy Efficiency Policy (NREEEP), developed in 2014 and approved in 2015, aims to enhance Nigeria's energy security and generation by 2000 megawatts, relying on large-scale renewable energy deployment, including hydropower, biomass, solar, wind, geothermal, wave, and tidal sources [43,128,129].

5. Addressing Key Challenges through Just Energy Transition Framework

It is recommended that Nigeria aggressively pursue the restructuring of its energy system, transitioning from a reliance on fossil fuels to the broad adoption of renewable energy. This shift aligns with the nation's objectives of enhancing energy security and stimulating economic growth. Nigeria has ambitiously targeted the installation of 10 GW of renewable energy by 2030 and aims to increase this capacity to 30 GW by 2050 [43]. Alongside these goals, Nigeria is committed to reducing carbon emissions by 50% from 2010 levels by 2030 and achieving net-zero emissions by 2060 [43]. To address energy poverty and drive socioeconomic growth, the country should strive for universal electricity access by 2030, with a focus on utilizing renewable sources for 90% of new connections [130]. To ensure the successful implementation of Nigeria's energy transition strategy, a structured and strategic plan is crucial, as depicted in Figure 9. The strategy will be guided by an inter-ministerial committee to align with both national priorities and international climate commitments.

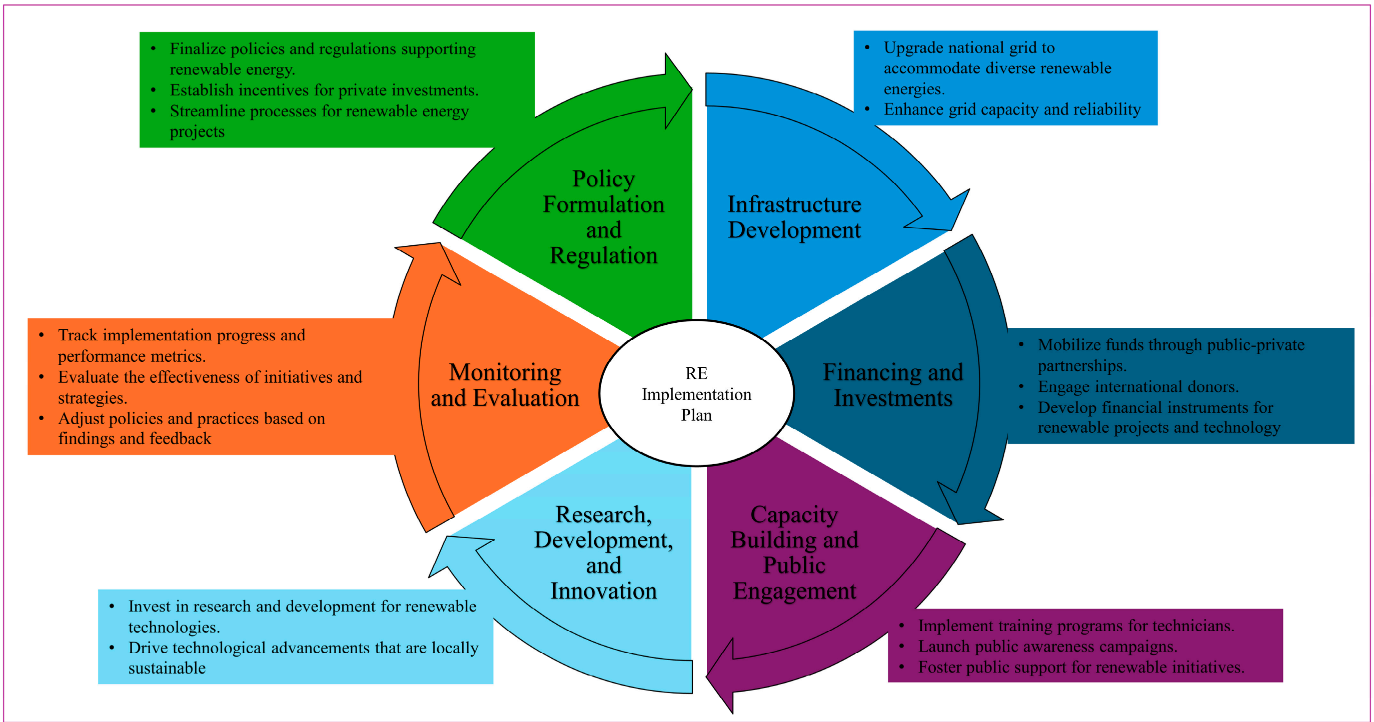

Figure 9. Implementation strategy for renewable energy in Nigeria.

The final stage of monitoring and evaluation is critical, ensuring that the strategy adapts to changing conditions and achieves the desired outcomes, paving the way for Nigeria to meet its ambitious energy goals effectively.

- Policy and Governance

For a successful transition, strengthening the regulatory framework to support renewable energy adoption and energy efficiency is crucial. By 2025, Nigeria should aim to fully enact and enforce all planned regulatory reforms. It is advised to mobilize USD 5 billion in renewable energy investments through financial incentives such as tax reliefs, feed-in tariffs, and direct subsidies, attracting both the domestic and international investments necessary to realize these ambitious energy targets [125].

- Infrastructure and Technology

To accommodate a diversified energy mix and integrate renewable energy effectively into the national grid, substantial infrastructure upgrades and expansions are essential. An investment target of USD 2 billion for grid modernization by 2030 will support an additional 20 GW of renewable capacity [129]. The goal is for renewables to make up 40% of Nigeria's energy mix by 2030, with a focus on scalable developments in solar, wind, biomass, and geothermal energy.

- Capacity Building and Public Engagement

Enhancing capacity-building initiatives and engaging the public is essential to support Nigeria's energy transition. The strategy should include training at least 500 experts from each state in Nigeria in the renewable energy sector by 2030 and conducting widespread public awareness campaigns to inform 60% of the population. These steps are vital to developing a skilled workforce and an informed public that actively support and participate in the energy transition.

- Financing and Investment

Securing adequate financing is pivotal to the success of Nigeria's energy transition. It is recommended to attract USD 10 billion in private investment and to leverage USD 3 billion in international climate finance by 2030 [115,122]. These funds are crucial for launching large-scale energy projects that meet Nigeria's renewable energy targets.

- Research and Development

To ensure the sustainability of the energy transition, Nigeria is committed to promoting research and development in renewable energy technologies. The government plans to allocate USD 500 million to R&D by 2030 [130], aiming to foster innovation and adapt technologies suitable for Nigeria's unique environmental and socioeconomic conditions. The goal is to register at least 100 new patents in renewable energy technologies by 2030, reinforcing Nigeria's position as a leader in energy innovation in Africa.

- Environmental and Social Justice

The transition strategy also emphasizes environmental and social justice, aiming to ensure that the shift to renewable energy sources contributes positively to societal welfare and reduces environmental degradation. By 2030, Nigeria plans to provide clean cooking solutions to 95% of households, and it plans to create 500,000 new jobs in the renewable energy sector by 2040 [121,130]. These efforts are geared towards reducing inequalities and enhancing the quality of life for all Nigerians, ensuring that the benefits of the energy transition are broadly shared across the country.

6. Conclusions

Nigeria's quest to resolve its energy crisis presents a complex interplay of challenges and opportunities. This study meticulously analyzes the longstanding obstacles plaguing the nation's power sector, including financial constraints, infrastructural degradation, endemic corruption, and the dearth of technical proficiency. However, abundant renewable resources, such as wind, hydropower, biomass, and solar energy, offer a beacon of hope, paving the way for a sustainable future. This study proposes a series of strategic recommendations to strengthen Nigeria's energy landscape. Central to this plan is the ambitious goal of generating 36% of its electricity from renewable sources by 2030. This target aligns with global sustainability initiatives while positioning Nigeria at the forefront of the renewable revolution in Africa. The strategy hinges on infrastructure improvements facilitated by significant financial investments and a comprehensive overhaul of regulatory frameworks, thereby ensuring a more robust and reliable energy grid. Furthermore, energy storage technologies, particularly lithium-ion batteries, emerge as the most suitable solution for Nigeria's growing solar sector, offering scalability and cost-efficiency. For grid-connected systems, pumped hydropower storage and thermal energy storage are well suited for balancing the supply and demand.

Emphasizing innovation through research and development, Nigeria is poised to lead in renewable energy technology, tailored to meet local needs while setting a global example. A dedicated monitoring and evaluation phase ensures strategy responsiveness to evolving energy demands and technological advancements. With a robust inter-ministerial committee, the comprehensive oversight and effective integration of renewable technologies into the national energy framework are ensured. These efforts are complemented by significant public engagement and capacity building, which are crucial for an informed and supportive populace. Central to Nigeria's strategic vision is the concept of a just energy transition, addressing social alongside environmental and economic objectives. This transition strategy is supported by a robust implementation framework that prioritizes transparency, inclusivity, and community engagement, enabling marginalized communities to benefit from clean energy advancements.

In striving for a future of sustainable and accessible energy, Nigeria goes beyond addressing its immediate energy needs to lay the groundwork for long-term economic growth and environmental stewardship. The envisioned energy transition represents not only a policy shift but also a transformative movement toward a more resilient and prosperous nation. As Nigeria mobilizes to reduce its reliance on fossil fuels and enhance its energy infrastructure, the global community observes, poised to learn from Nigeria's bold, decisive action in addressing complex energy challenges. This transition, driven by ambition and pragmatism, promises to redefine Nigeria's socioeconomic trajectory and provides a sustainable model for other developing nations to emulate.

Author Contributions: M.A.A. contributed to the writing, methodology, formal analysis, and validation. A.M.O. contributed to the writing and formal analysis. H.O.S. contributed to the writing and formal analysis. A.O.Y. contributed to the writing and formal analysis. N.N.S. contributed to the data curation, writing, and formal analysis. Z.A.S. contributed to the formal analysis and reviewing and editing. J.-S.H. contributed to the investigation, supervision, funding acquisition, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF), a grant funded by the Korean government Ministry of Science and ICT (MSIT) (No. NRF-2021R1A5A8033165), and by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry and Energy (MOTIE) of the Republic of Korea (No. 20224000000150).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Nitte, I.S. Global energy transition and its implications on energy security in nigeria: A critical review. *EPRA Int. J. Clim. Resour. Econ. Rev.* **2023**, *11*, 1–9. [CrossRef]
2. Chongkon, Z. An Overview of Renewable Energy Development in Nigeria over the Years: Challenges and Control Measures. *ScienceOpen*, 2023; *preprints*.
3. Golobish, S.; Yeganyan, R.; Tan, N.; Cannone, C.; Howells, M. The Burden of the Broken Grid: Modelling Improved Power-sector Reliability to Support Low Carbon Development in Nigeria. 2023. Available online: https://www.researchgate.net/publication/369995455_The_Burden_of_the_Broken_Grid_Modelling_improved_power-sector_reliability_to_support_low_carbon_development_in_Nigeria (accessed on 5 August 2024).

4. Ole, N.C.; Pereira, E.G.; Oniemola, P.K.; Loureiro, G.K. *Regulatory Support for Off-Grid Renewable Electricity*; Taylor & Francis: London, UK, 2023.
5. Jack, J.T.C.B.; Jack, B. Nigeria's Energy Crisis and the Sustainability Question. *Soc. Health Sci.* **2022**, *20*, 19. [CrossRef]
6. Oyedepo, S.O. Energy in perspective of sustainable development in Nigeria. *Sustain. Energy* **2013**, *1*, 14–25.
7. Oyedokun, J.A.; Fasina, E.T.; Adebanji, B.; Abe, A. Electricity challenges in Nigeria: Renewable energy a way forward. *Glob. J. Eng. Technol. Adv.* **2022**, *11*, 16–23. [CrossRef]
8. TANSU, A.; Ogungbemi, A.T.; Hocanin, F.T. The challenges and serviceability of solar power: Suggestion on solving the Nigeria energy crisis. *Int. J. Energy Stud.* **2022**, *7*, 127–141. [CrossRef]
9. Ogunniyi, O.J.; Oni, T.O.; Ikubanni, P.P.; Aliyu, S.J.; Ajisegiri, E.A.; Ibikunle, R.A.; Adekanye, T.A.; Adeleke, A.A.; Ajewole, J.B.; Ogundipe, O.L.; et al. *Prospects for Nigerian Electricity Production from Renewable Energy*; IEEE: New York, NY, USA, 2023; pp. 1–6.
10. Okoh, A.S.; Okpanachi, E. Transcending energy transition complexities in building a carbon-neutral economy: The case of Nigeria. *Clean. Energy Syst.* **2023**, *6*, 100069. [CrossRef]
11. Lawal, O.A.; Jimoh, A.A.; Abdulkadir, Z.A.; Bello, A.B.; Balogun, M.O.; Atanda, A.R. *Mitigating the Challenge of Energy Crisis via Energy Audit and Efficiency Measures: A Case of a Household in Nigeria*; IEEE: New York, NY, USA, 2023; pp. 218–223.
12. Abdullahi, Y.; Kehinde, A.O. Drivers, Enablers, Barriers and Technologies (DEBT) For Low-Energy Public Housing Delivery in Nigeria. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2023**, *29*, 115–127. [CrossRef]
13. IRENA. *Renewable Energy Roadmap 2030*; IRENA: Masdar City, United Arab Emirates, 2016.
14. Umeji, G.; Agu, A.O.; Eleanya, E.; Chinedum, E.M.; Nwabugwu, O.O.; Mbadiwe, T. Renewable Energy Consumption and Economic Growth in Nigeria. *Afr. J. Soc. Sci. Humanit. Res.* **2023**, *6*, 34–48.
15. Jekayinfa, S.O.; Orisaleye, J.I.; Pecenka, R. An assessment of potential resources for biomass energy in Nigeria. *Resources* **2020**, *9*, 92. [CrossRef]
16. Ukoba, M.; Diemuodeke, E.; Briggs, T.; Imran, M.; Owebor, K.; Nwachukwu, C. Geographic information systems (GIS) approach for assessing the biomass energy potential and identification of appropriate biomass conversion technologies in Nigeria. *Biomass Bioenergy* **2023**, *170*, 106726. [CrossRef]
17. Ezealigo, U.S.; Otoijamun, I.; Onwualu, A.P. *Electricity and Biofuel Production from Biomass in Nigeria: Prospects, Challenges and Way Forward*; IOP Publishing: Bristol, UK, 2021; p. 012035.
18. Solar Report Nigeria. 2021. Available online: https://www.rvo.nl/sites/default/files/2021/06/Solar-Report-Nigeria.pdf (accessed on 5 August 2024).
19. Ilenikhena, B.P.; Ezemonye, L.; Ilenikhena, P. Solar Energy Applications in Nigeria. Available online: https://www.semanticscholar.org/paper/SOLAR-ENERGY-APPLICATIONS-IN-NIGERIA-Ilenikhena-Ezemonye/dde91a65a41f3fd2a45ccd4077ce54e900ed5105 (accessed on 5 August 2024).
20. Brimmo, A.T.; Sodiq, A.; Sofela, S.; Kolo, I. Sustainable energy development in Nigeria: Wind, hydropower, geothermal and nuclear (Vol. 1). *Renew. Sustain. Energy Rev.* **2017**, *74*, 474–490. [CrossRef]
21. Fasipe, O.; Izinyon, O.; Ehiorobo, J. Hydropower potential assessment using spatial technology and hydrological modelling in Nigeria river basin. *Renew. Energy* **2021**, *178*, 960–976. [CrossRef]
22. Edeh, I.; Okpo, S.O. Biomass to Biofuels: A sure Sustainable Energy Strategy in Nigeria. *Petro Chem Indus Intern* **2023**, *6*, 106–117. Available online: https://www.opastpublishers.com/open-access-articles/biomass-to-biofuels-a-sure-sustainable-energy-strategy-in-nigeria.pdf (accessed on 11 January 2024).
23. Adeleke, A.A.; Petrus, N.; Ayuba, S.; Yahya, A.M.; Ikubanni, P.P.; Okafor, I.S.; Emmanuel, S.S.; Olosho, A.I.; Adesibikan, A.A. Nigerian Biomass for Bioenergy Applications: A Review on the Potential and Challenges. *J. Renew. Mater.* **2023**, *11*, 43915. [CrossRef]
24. Ishola, M.M.; Brandberg, T.; Sanni, S.A.; Taherzadeh, M.J. Biofuels in Nigeria: A critical and strategic evaluation. *Renew. Energy* **2013**, *55*, 554–560. [CrossRef]
25. Shiru, S.; Shiru, M.S. Towards commercialization of third-generation biofuel industry for sustainable energy production in Nigeria. *ChemBioEng Rev.* **2021**, *8*, 593–611. [CrossRef]
26. Łaska, G.; Ige, A.R. A Review: Assessment of Domestic Solid Fuel Sources in Nigeria. *Energies* **2023**, *16*, 4722. [CrossRef]
27. Sasongko, N.A.; Putra, N.G.; Wardani, M.L.D. Review of types of biomass as a fuel-combustion feedstock and their characteristics. *Adv. Food Sci. Sustain. Agric. Agroindustrial Eng.* **2023**, *6*, 170–184. [CrossRef]
28. Ong, H.C.; Chen, W.-H.; Farooq, A.; Gan, Y.Y.; Lee, K.T.; Ashokkumar, V. Catalytic thermochemical conversion of biomass for biofuel production: A comprehensive review. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109266. [CrossRef]
29. Ajala, E.O.; Ighalo, J.O.; Ajala, M.A.; Adeniyi, A.G.; Ayanshola, A.M. Sugarcane bagasse: A biomass sufficiently applied for improving global energy, environment and economic sustainability. *Bioresour. Bioprocess.* **2021**, *8*, 87. [CrossRef] [PubMed]
30. Onochie, U.P.; Ofomatah, A.C.; Onwurah, C.; Tyopine, A.A.; Akingba, O.O.; Kubeynje, B.F.; Aluma, C.C.; Alozie, C. *Potentials of Biomass Waste Resources with Respect to Their Calorific Value, Proximate and Ultimate Analysis for Energy Utilization*; IOP Publishing: Bristol, UK, 2023; p. 012012. Available online: https://iopscience.iop.org/article/10.1088/1755-1315/1178/1/012012/meta (accessed on 11 January 2024).
31. Adeoti, O.; Adegboyega, T.D.; Ayelegun, T.A. An Assessment of Nigeria Biogas Potential from Agricultural Wastes. *Energy Sources* **2001**, *23*, 63–68. [CrossRef]

32. Adeoti, O.; Ayelegun, T.; Osho, S. Nigeria biogas potential from livestock manure and its estimated climate value. *Renew. Sustain. Energy Rev.* **2014**, *37*, 243–248. [CrossRef]
33. Okoro, E.E.; Okafor, I.S.; Igwilo, K.C.; Orodu, K.B.; Mamudu, A.O. Sustainable biogas production from waste in potential states in Nigeria–alternative source of energy. *J. Contemp. Afr. Stud.* **2020**, *38*, 627–643. [CrossRef]
34. Akinbami, J.-F.; Ilori, M.O.; Oyebisi, T.O.; Akinwumi, I.O.; Adeoti, O. Biogas energy use in Nigeria: Current status, future prospects and policy implications. *Renew. Sustain. Energy Rev.* **2001**, *5*, 97–112. Available online: https://www.sciencedirect.com/science/article/pii/S1364032100000058 (accessed on 11 January 2024). [CrossRef]
35. Riagbayire, F.; Nayem, Z. Biogas: An Alternative Energy Source for Domestic and Small-Scale Industrial Use in Nigeria. *Am. J. Innov. Sci. Eng.* **2023**, *2*, 8–16. [CrossRef]
36. Okokpujie, I.P.; Okokpujie, K.; Omidiora, O.; Oyewole, H.O.; Ikumapayi, O.M.; Emuowhochere, T.O. Benchmarking and Multi-Criteria Decision Analysis Towards Developing a Sustainable Policy of Just in Time Production of Biogas in Nigeria. *Int. J. Sustain. Dev. Plan.* **2022**, *17*, 433–440. Available online: https://www.researchgate.net/profile/Omolayo-Ikumapayi/publication/360255874_Benchmarking_and_Multi-Criteria_Decision_Analysis_Towards_Developing_a_Sustainable_Policy_of_Just_in_Time_Production_of_Biogas_in_Nigeria/links/626b768705d79a3968aa83c0/Benchmarking-and-Multi-Criteria-Decision-Analysis-Towards-Developing-a-Sustainable-Policy-of-Just-in-Time-Production-of-Biogas-in-Nigeria.pdf (accessed on 11 January 2024). [CrossRef]
37. Johnson, E.N.; Esther, O.E.; Hilary, I.W.; Dozie, E.A. Design Simulation Analysis and Enhancement of Nigeria Biogas to Connect That of Natural Gas Netting Capacity and Model. *Int. J. Res. Appl. Sci. Eng. Technol.* **2022**, *10*, 516–521. [CrossRef]
38. Ibeaja, A.C.E.; Nwaogazie, I.L.; Udeh, N.U. Temperature Effect on Biogas Production from Co-digestion of Food Waste, Potash and Cow Dung. *J. Eng. Res. Rep.* **2023**, *24*, 21–28. Available online: https://www.researchgate.net/profile/Ify-Nwaogazie/publication/368909192_Temperature_Effect_on_Biogas_Production_from_Co-digestion_of_Food_Waste_Potash_and_Cow_Dung/links/640a4cd4a1b72772e4e57613/Temperature-Effect-on-Biogas-Production-from-Co-digestion-of-Food-Waste-Potash-and-Cow-Dung.pdf (accessed on 11 January 2024).
39. Amah, V.E.; Udeh, N.; Ejuvwevwo, E.T. Biogas Production from Co-digestion of Cattle Manure, Oryza sativa and Phaseolus vulgaris in Plug Flow Digester. *Adv. Res.* **2023**, *24*, 36–46. [CrossRef]
40. Wind Energy. Available online: https://www.irena.org/Energy-Transition/Technology/Wind-energy#:~:text=Global%20installed%20wind-generation%20capacity,according%20to%20IRENA%E2%80%99s%20latest%20data (accessed on 11 January 2024).
41. Wind Energy. Available online: https://www.irena.org/Energy-Transition/Technology/Wind-energy (accessed on 11 January 2024).
42. Top 10 Countries in Wind Energy Capacity | REVE News of the Wind Sector in Spain and in the World. Available online: https://www.evwind.es/2021/05/24/top-10-countries-in-wind-energy-capacity/80896 (accessed on 11 January 2024).
43. Somoye, O.A. Energy crisis and renewable energy potentials in Nigeria: A review. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113794. [CrossRef]
44. Adekoya, L.; Adewale, A. Wind energy potential of Nigeria. *Renew. Energy* **1992**, *2*, 35–39. [CrossRef]
45. Ojosu, J.; Salawu, R. A survey of wind energy potential in Nigeria. *Sol. Wind. Technol.* **1990**, *7*, 155–167. [CrossRef]
46. Adedipe, O.; Abolarin, M.; Mamman, R.O. A Review of Onshore and Offshore Wind Energy Potential in Nigeria. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *413*, 012039. [CrossRef]
47. Mukasa, A.D.; Mutambatsere, E.; Arvanitis, Y.; Triki, T. Development of Wind Energy in Africa. Available online: https://www.afdb.org/fileadmin/uploads/afdb/Documents/Knowledge/AEC%202012%20-%20Wind%20Energy%20Development%20in%20Africa.pdf (accessed on 5 August 2024).
48. Ajayi, O.O. The Potential for Wind Energy in Nigeria. *Wind. Eng.* **2010**, *34*, 303–311. [CrossRef]
49. Al-Hinai, A.; Charabi, Y.; Kaboli, S.H.A. Offshore Wind Energy Resource Assessment across the Territory of Oman: A Spatial-Temporal Data Analysis. *Sustainability* **2021**, *13*, 2862. [CrossRef]
50. Ohunakin, O.S. Wind resource evaluation in six selected high altitude locations in Nigeria. *Renew. Energy* **2011**, *36*, 3273–3281. [CrossRef]
51. Adaramola, M.; Oyewola, O. Evaluating the performance of wind turbines in selected locations in Oyo state, Nigeria. *Renew. Energy* **2011**, *36*, 3297–3304. [CrossRef]
52. Fagbenle, R.; Katende, J.; Ajayi, O.; Okeniyi, J. Assessment of wind energy potential of two sites in North-East, Nigeria. *Renew. Energy* **2011**, *36*, 1277–1283. [CrossRef]
53. Ben, U.C.; Akpan, A.E.; Mbonu, C.C.; Ufuafuonye, C.H. Integrated technical analysis of wind speed data for wind energy potential assessment in parts of southern and central Nigeria. *Clean. Eng. Technol.* **2021**, *2*, 100049. [CrossRef]
54. Ayodele, T.; Ogunjuyigbe, A.; Amusan, T. Wind power utilization assessment and economic analysis of wind turbines across fifteen locations in the six geographical zones of Nigeria. *J. Clean. Prod.* **2016**, *129*, 341–349. [CrossRef]
55. Ayodele, T.; Ogunjuyigbe, A.; Amusan, T. Techno-economic analysis of utilizing wind energy for water pumping in some selected communities of Oyo State, Nigeria. *Renew. Sustain. Energy Rev.* **2018**, *91*, 335–343. [CrossRef]
56. Ayodele, T.; Ogunjuyigbe, A.; Odigie, O.; Munda, J. A multi-criteria GIS based model for wind farm site selection using interval type-2 fuzzy analytic hierarchy process: The case study of Nigeria. *Appl. Energy* **2018**, *228*, 1853–1869. [CrossRef]

57. Ohunakin, S.O.; Ojolo, S.J.; Ogunsina, S.B.; Dinrifo, R.R. Analysis of cost estimation and wind energy evaluation using wind energy conversion systems (WECS) for electricity generation in six selected high altitude locations in Nigeria. *Energy Policy* **2012**, *48*, 594–600. [CrossRef]
58. Adaramola, M.; Paul, S.; Oyedepo, S. Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria. *Energy Convers. Manag.* **2011**, *52*, 3363–3368. [CrossRef]
59. Effiom, S.; Nwankwojike, B.; Abam, F. Economic cost evaluation on the viability of offshore wind turbine farms in Nigeria. *Energy Rep.* **2016**, *2*, 48–53. [CrossRef]
60. Adetokun, B.B.; Muriithi, C.M. Impact of integrating large-scale DFIG-based wind energy conversion system on the voltage stability of weak national grids: A case study of the Nigerian power grid. *Energy Rep.* **2021**, *7*, 654–666. [CrossRef]
61. Aririguzo, J.C.; Ekwe, E.B. Weibull distribution analysis of wind energy prospect for Umudike, Nigeria for power generation. *Robot. Comput. Manuf.* **2019**, *55*, 160–163. [CrossRef]
62. Salisu, S.; Mustafa, M.W.; Olatomiwa, L.; Mohammed, O.O. Assessment of technical and economic feasibility for a hybrid PV-wind-diesel-battery energy system in a remote community of north central Nigeria. *Alex. Eng. J.* **2019**, *58*, 1103–1118. [CrossRef]
63. Ezekwem, C.; Muthusamy, S. Feasibility study of integrating the renewable energy system for increased electricity access: A case study of Choba community in Nigeria. *Sci. Afr.* **2023**, *21*, e01781. [CrossRef]
64. Babatunde, O.; Munda, J.; Hamam, Y. Off-grid hybrid photovoltaic–micro wind turbine renewable energy system with hydrogen and battery storage: Effects of sun tracking technologies. *Energy Convers. Manag.* **2022**, *255*, 115335. [CrossRef]
65. Adetunla, A.; Rominiyi, O.; Adaramola, B.; Adeoye, A. Development of a wind turbine for a hybrid solar-wind power system. *Heliyon* **2022**, *8*, e11458. [CrossRef]
66. Babatunde, O.; Munda, J.; Hamam, Y. Hybridized off-grid fuel cell/wind/solar PV/battery for energy generation in a small household: A multi-criteria perspective. *Int. J. Hydrogen Energy* **2022**, *47*, 6437–6452. [CrossRef]
67. Tsutsui, M.; Hsu, W.; Yokota, K.; Leong, I.W.; Daiguji, H.; Kawai, T. Scalability of nanopore osmotic energy conversion. *Exploration* **2024**, *4*, 20220110. [CrossRef]
68. Li, R.-C.; Zhang, X.-Y.; Qu, Z.-Y.; Liu, F.-Y.; Xu, Q.-Q.; Hu, Z.-X.; Li, J.-W.; Ghazzal, M.-N.; Yu, J.-L. One-step controlled electrodeposition nickel sulfides heterointerfaces favoring the desorption of hydroxyl groups for efficient hydrogen generation. *Rare Met.* **2024**, *43*, 4377–4386. [CrossRef]
69. IHA. *2022 Hydropower Status Report*; International Hydropower Association: London, UK, 2022; pp. 1–52.
70. World Hydropower Outlook. Available online: https://www.hydropower.org/publications/2023-world-hydropower-outlook (accessed on 17 March 2024).
71. Hydropower Generation by Country 2022 | Statista. Available online: https://www.statista.com/statistics/474799/global-hydropower-generation-by-major-country/ (accessed on 17 March 2024).
72. Ugwu, C.O.; Ozor, P.A.; Mbohwa, C. Small hydropower as a source of clean and local energy in Nigeria: Prospects and challenges. *Fuel Commun.* **2022**, *10*, 100046. [CrossRef]
73. ECN. *Energy Commission of Nigeria, Federal Republic of Nigeria. National Energy Masterplan*; Energy Commission of Nigeria: Abuja, Nigeria, 2022.
74. Energy Commission of Nigeria. *Energy Commission of Nigeria Federal Republic of Nigeria [Draft Revised Edition]*; Energy Commission of Nigeria: Abuja, Nigeria, 2018.
75. IRENA. *Renewable Capacity*; IRENA: Masdar City, United Arab Emirates, 2021.
76. General Hydropower–Renewables First–The Renewable Energy Company. Available online: https://renewablesfirst.co.uk/renewable-energy-technologies/hydropower/hydropower-learning-centre/general-hydropower/#top (accessed on 17 March 2024).
77. Owebor, K.; Diemuodeke, E.; Briggs, T.; Imran, M. Power Situation and renewable energy potentials in Nigeria–A case for integrated multi-generation technology. *Renew. Energy* **2021**, *177*, 773–796. [CrossRef]
78. Mohammed, Y.; Mustafa, M.; Bashir, N.; Mokhtar, A. Renewable energy resources for distributed power generation in Nigeria: A review of the potential. *Renew. Sustain. Energy Rev.* **2013**, *22*, 257–268. [CrossRef]
79. Igbinovia, F. An overview of Renewable energy potential in Nigeria: Prospects, Challenge and the Way forward. *Energ. J.* **2014**, *46*, 570–579.
80. Oyinna, B.; Okedu, K.E.; Diemuodeke, O.E.; David, L.E.; Negedu, I.O.; Osemudiamen, E.A.; Colak, I.; Kalam, A. Assessing small hydropower sites in Nigeria for sustainable development using ArcGIS. *Energy Rep.* **2023**, *10*, 2889–2898. [CrossRef]
81. International Renewable Energy Agency, Renewable Energy Statistics 2022 Statistiques D'Energie Renouvelable 2022 Estadisticas De Energia Renovablle 2022. 2022. Available online: https://www.irena.org/publications/2022/Jul/Renewable-Energy-Statistics-2022 (accessed on 5 August 2024).
82. IRENA. IRENA_REMap_Nigeria_2023. 2023. Available online: https://www.irena.org/Publications/2023/Jan/Renewable-Energy-Roadmap-Nigeria (accessed on 5 August 2024).
83. Shaaban, M.; Petinrin, J. Renewable energy potentials in Nigeria: Meeting rural energy needs. *Renew. Sustain. Energy Rev.* **2014**, *29*, 72–84. [CrossRef]
84. Ogueri, K. Renewable Energy Sources. Its Benefits, Potentials and Challenges in Nigeria. *J. Energy Technol. Policy* **2015**, *5*, 21–25.

85. Elum, Z.A.; Mjimba, V. Potential and challenges of renewable energy development in promoting a green economy in Nigeria. *Afr. Rev.* **2020**, *12*, 172–191. [CrossRef]
86. Ogunbiyi, O.; Ahmed, M.O.; Adesina, L.M.; Olufeagba, B.J. Numerical Approximation of Indirect Optimal Control of Jebba Hydroelectric Power Plant. *ARPN J. Eng. Appl. Sci.* **2021**, *16*, 135–141.
87. Energy Utilization and Renewable Energy Sources. Available online: https://www.iea.org/reports/renewables-2023/electricity (accessed on 5 August 2024).
88. Muhammadu, M.M.; Usman, J. Small Hydropower Development in North-Central of Nigeria: An Assessment. *J. Adv. Res. Appl. Mech.* **2020**, *69*, 7–16. [CrossRef]
89. Nigerian Electricity Regulatory Commission; District, C.B.; Abuja, G. Annual Report & Accounts. Available online: https://nerc.gov.ng/media/nerc-annual-report-2023/ (accessed on 5 August 2024).
90. Nigerian Electricity Regulatory Commission. Nigerian Electricity Regulatory Electricity on Demand Quarterly Report Second Quarter 2020. 2020. Available online: https://nerc.gov.ng/wp-content/uploads/2020/10/Quarterly%20Reports_2020Q1_FINAL.pdf (accessed on 5 August 2024).
91. Okedu, K.E.; Uhunmwangho, R.; Odje, M. Harnessing the potential of small hydro power in Cross River state of Southern Nigeria. *Sustain. Energy Technol. Assess.* **2020**, *37*, 100617. [CrossRef]
92. Nchege, J.; Okpalaoka, C. Hydroelectric production and energy consumption in Nigeria: Problems and solutions. *Renew. Energy* **2023**, *219*, 119548. [CrossRef]
93. Fakehinde, O.B.; Fayomi, O.S.; Efemwenkieki, U.K.; Babaremu, K.O.; Kolawole, D.O.; Oyedepo, S.O. Viability of Hydroelectricity in Nigeria and the Future Prospect. *Energy Procedia* **2019**, *157*, 871–878. [CrossRef]
94. Pavanelli, J.M.M.; Sang, E.V.; de Oliveira, C.E.; Campos, F.d.R.; Lazaro, L.L.B.; Edomah, N.; Igari, A.T. An institutional framework for energy transitions: Lessons from the Nigerian electricity industry history. *Energy Res. Soc. Sci.* **2023**, *97*, 102994. [CrossRef]
95. Chanchangi, Y.N.; Adu, F.; Ghosh, A.; Sundaram, S.; Mallick, T.K. Nigeria's energy review: Focusing on solar energy potential and penetration. *Environ. Dev. Sustain.* **2023**, *25*, 5755–5796. [CrossRef]
96. Solar Energy in Nigeria; Economic Potentials, Problems, Prospects. Available online: https://infoguidenigeria.com/solar-energy-in-nigeria/ (accessed on 12 January 2024).
97. Nigeria's PV Potential–Everoze. Available online: https://everoze.com/nigerias-pv-potential/ (accessed on 12 January 2024).
98. Ozoegwu, C.G.; Akpan, P.U. A review and appraisal of Nigeria's solar energy policy objectives and strategies against the backdrop of the renewable energy policy of the Economic Community of West African States. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110887. [CrossRef]
99. Renewable Energy Potential in Nigeria. Available online: https://climate-pact.europa.eu/index_en (accessed on 19 September 2024).
100. Nigeria's Solar Energy Potential Higher than Current Consumption—Ikeja Electric–Vanguard News. Available online: https://www.vanguardngr.com/2023/08/nigerias-solar-energy-potential-higher-than-current-consumption-ikeja-electric/ (accessed on 12 January 2024).
101. Bamisile, O.; Dagbasi, M.; Babatunde, A.; Ayodele, O. A review of renewable energy potential in Nigeria; Solar power development over the years. *Eng. Appl. Sci. Res.* **2017**, *44*, 242–248. [CrossRef]
102. Bawonda, F.I.; Adefarati, T. Evaluation of solar energy potential in six geopolitical regions of Nigeria using analytical and simulation techniques. *Energy Convers. Manag.* **2023**, *290*, 117193. [CrossRef]
103. Osinowo, A.A.; Okogbue, E.C.; Ogungbenro, S.B.; Fashanu, O. Analysis of Global Solar Irradiance over Climatic Zones in Nigeria for Solar Energy Applications. *J. Sol. Energy* **2015**, *2015*, 1–9. [CrossRef]
104. Ohunakin, O.S.; Adaramola, M.S.; Oyewola, O.M.; Matthew, O.J.; Fagbenle, R.O. The effect of climate change on solar radiation in Nigeria. *Sol. Energy* **2015**, *116*, 272–286. [CrossRef]
105. Ogunjo, S.T.; A Obafaye, A.; Rabiu, A.B. Solar energy potentials in different climatic zones of Nigeria. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1032*, 012040. [CrossRef]
106. Solar Resource Maps and GIS Data for 200+ Countries | Solargis. Available online: https://solargis.com/maps-and-gis-data/download/nigeria (accessed on 12 January 2024).
107. Diyoke, C.; Ngwaka, U.; Ugwu, K. A comprehensive analysis on the grid-tied solar photovoltaics for clean energy mix and supply in Nigeria's on-grid power. *J. Energy Syst.* **2023**, *7*, 1–17. [CrossRef]
108. Okoro, U.K.; Chineke, T.C. Whistleblowing on photovoltaic operations in Nigeria: Panacea for sustainable development. *Bull. Natl. Res. Cent.* **2021**, *45*, 1–8. [CrossRef]
109. Elegeonye, H.; Ohunakin, O. Techno-Economic Optimization and Energy Scenario Analysis of Isolated Mini-Grid Systems in Nigeria. Ph.D. Thesis, Pan Afrrican University, Tlemcen, Algeria, 2021.
110. Zarmai, J.T.; Alabi, I.I.; Ebisine, E.E.; Zarmai, M.T.; Irefu, O.D. Design and Techno-Economic Evaluation of a Hybrid Mini-grid System for an Academic Institution. *J. Energy Power Technol.* **2024**, *6*, 1–16. [CrossRef]
111. Emezirinwune, M.U.; Adejumobi, I.A.; Adebisi, O.I.; Akinboro, F.G. Synergizing hybrid renewable energy systems and sustainable agriculture for rural development in Nigeria. *e-Prime* **2024**, *7*, 100492. [CrossRef]
112. Owolabi, A.B.; Yakub, A.O.; Luqman, R.; Same, N.N.; Suh, D. Performance Assessment of Four Grid-Connected Solar Photovoltaic Technologies under Similar Environmental Conditions in Nigeria. *Int. J. Energy Res.* **2023**, *2023*, 1–19. [CrossRef]

113. Amole, A.O.; Owosibo, R.A.; Adewuyi, O.B.; Oladipo, S.; Imarhiagbe, N.O. Comparative analysis of control strategies for solar photovoltaic/diesel power system for stand-alone applications. *Renew. Energy* **2023**, *226*, 119717. [CrossRef]
114. IRENA; CPI. Global Landscape of Renewable Energy Finance 2023. 2023. Available online: www.irena.org/publications (accessed on 19 September 2024).
115. International Renewable Energy Agency. Renewable Energy Market Analysis: Africa and its Regions. 2022. Available online: www.afdb.org (accessed on 19 September 2024).
116. Renewables Can Provide Nearly 60 Per Cent of Nigeria's Energy Demand by 2050. Available online: https://www.irena.org/News/pressreleases/2023/Jan/Renewables-Can-Provide-Nearly-60-Per-Cent-of-Nigerias-Energy-Demand-by-2050 (accessed on 19 September 2024).
117. ZUNGERU HYDROPOWER PROJECT–Bureau of Public Enterprises (BPE). Available online: https://www.bpe.gov.ng/zungeru-hydropower-project/ (accessed on 19 September 2024).
118. Nigeria's Energy Crisis: Shedding Light on Corruption, Obstacles, Reforms for Energy Transition–EnviroNews–Latest Environment News, Climate Change, Renewable Energy. Available online: https://www.environewsnigeria.com/nigerias-energy-crisis-shedding-light-on-corruption-obstacles-reforms-for-energy-transition/ (accessed on 19 September 2024).
119. Power Generation Costs. Available online: https://www.irena.org/Energy-Transition/Technology/Power-generation-costs (accessed on 19 September 2024).
120. International Renewable Energy Agency. Renewable Power Generation Costs in 2022. 2023. Available online: https://www.irena.org (accessed on 19 September 2024).
121. International Renewable Energy Agency. Renewable Energy Roadmap Nigeria. 2023. Available online: https://www.irena.org (accessed on 19 September 2024).
122. International Renewable Energy Agency. *Renewable Energy Roadmap Nigeria Summary of Key Recommendations and Findings*; International Renewable Energy Agency: Abu Dhabi, UAE, 2023.
123. Acen, C.; Bamisile, O.; Adedeji, M.; Cai, D.; Dagbasi, M.; Hu, Y.; Staffell, I. Energy, exergy, and exergoeconomic cost optimization of wind-biomass multi-energy systems integrated for hydrogen production. *J. Therm. Anal. Calorim.* **2024**, *149*, 8799–8812. [CrossRef]
124. Kao, S.C.; McManamay, R.A.; Stewart, K.M.; Samu, N.M.; Hadjerioua, B.; DeNeale, S.T.; Yeasmin, D.; Pasha, M.F.K.; Oubeidillah, A.A.; Smith, B.T. *New Stream-reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States*; Oak Ridge National Lab.: Oak Ridge, TN, USA, 2014. [CrossRef]
125. Roy, P.; Iwuamadi, K.C.; Ibrahim, J. Breaking the Cycle of Corruption in Nigeria's Electricity Sector: A Political Settlements Analysis. 2020. Available online: https://www.semanticscholar.org/paper/Breaking-the-cycle-of-corruption-in-Nigeria%E2%80%99s-a-Roy-Iwuamadi/98054fc290c554e34ec9e7f3cd81ace84bee31d4 (accessed on 5 August 2024).
126. Marcellus, I.O. Development Planning in Nigeria: Reflections on the National Economic Empowerment and Development Strategy (Needs) 2003-2007. *J. Soc. Sci.* **2009**, *20*, 197–210. [CrossRef]
127. Abuja, G. Energy Commission of Nigeria Federal Ministry of Science, Technology and Innovation Federal Republic of Nigeria National Energy Policy Revised Edition Energy Commission of Nigeria 2022 Energy Commission of Nigeria Plot 701c Central Business District. Available online: https://www.energy.gov.ng/Energy_Policies_Plan/APPROVED_NEMP_2022.pdf (accessed on 5 August 2024).
128. Emodi, N.V.; Ebele, N.E. Policies Enhancing Renewable Energy Development and Implications for Nigeria. *Sustain. Energy* **2016**, *4*, 7–16. [CrossRef]
129. Obada, D.O.; Muhammad, M.; Tajiri, S.B.; Kekung, M.O.; Abolade, S.A.; Akinpelu, S.B.; Akande, A. A review of renewable energy resources in Nigeria for climate change mitigation. *Case Stud. Chem. Environ. Eng.* **2024**, *9*, 100669. [CrossRef]
130. Nigeria Energy Transition Plan. Available online: https://www.energytransition.gov.ng/ (accessed on 19 September 2024).
131. Energy Commission of Nigeria. Available online: https://energy.gov.ng/energy_laws.php (accessed on 2 May 2024).