Assessing the Impact of Climate Change on Wind Energy Potential in Nigeria's Coastal States: A Future Perspective

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ABSTRACT

Wind power represents a highly promising renewable energy source for mitigating greenhouse gas emissions, and the world is swiftly transitioning towards more sustainable energy alternatives. Despite their proximity to ample wind resources, Nigeria's coastal regions are not fully capitalising on them. This study examines the impact of climate change on wind energy potential. This study investigates the rising interest in wind energy within Nigeria's coastal states and evaluates climate-related challenges, including alterations in wind patterns, structural shortcomings, and the escalating incidence of extreme weather events. Presently, the majority of Nigeria's energy infrastructure is dependent on fossil fuels and hydropower. This paper explores the effects of climate variability on wind energy production and the alterations in wind patterns through a comprehensive analysis of scientific studies and climate models. It suggests ways to make wind energy in Nigeria more resilient and sustainable by combining new technologies with existing policy frameworks. The energy transition in Nigeria is based on lessons learnt from other countries with comparable climates, such as Brazil and Southern California. The results highlight the critical importance of investing in research, smart grid technology, and hybrid renewable system development to make the most of wind energy. The study concludes that in order to construct a long-term wind energy infrastructure in Nigeria that can endure the effects of climate change and help achieve global climate goals, a multi-pronged strategy involving technology, legislation, and community involvement is necessary.

Keywords: Wind energy, Climate change, Coastal Nigeria, Renewable energy infrastructure.

INTRODUCTION

Despite the crucial need for long-term, clean energy solutions, the globe is rapidly shifting towards greener energy sources. This transformation is propelled by the growing concern about climate change, emphasising the need for varied energy portfolios to fulfil present demands and withstand future challenges [1]. This puts the Nigerian coastal states at the forefront of efforts to harness wind and other renewable energy. Nigeria's exploration into wind energy is relatively nascent, with most of its energy infrastructure focused on fossil fuels and hydropower [2]. As of the last comprehensive update by Attabo et al., [3], there are a few pilot projects and planned developments for wind energy, particularly in coastal areas where wind resources are more abundant. The Katsina wind farm is an example of moving towards harnessing wind. Although it's not in a coastal region, it indicates a growing interest in wind energy [4]. Coastal states, due to their proximity to the Atlantic Ocean, are considered prime locations for wind farms. However, infrastructure development is challenged by financing, technology transfer, and policy frameworks [3]. Nigeria's installed capacity for wind energy is minimal compared to the country's potential. With Nigeria's vast coastline, the potential for wind energy is significant yet underutilized [5]. The capacity factors for existing or proposed projects are not well-documented. Still, they are expected to be competitive, given the global averages in similar climatic zones like Cameroon, as documented by Koholé et al., [6]. The region's wind energy infrastructure is still in its early stages; thus, it's reasonable to expect low utilisation rates.

The effects of climate change on Nigeria's agricultural sector, water supply, and people's ability to make a living are far-reaching and complex. There has been a noticeable tendency towards higher average temperatures, more erratic rainfall patterns, and more frequent severe weather [7]. Due to these changes, wind patterns, an essential renewable energy component, are susceptible to shift. Because of their heightened vulnerability to rising sea levels and warmer temperatures, coastal areas confront distinct threats to the viability and effectiveness of wind energy projects [8].

Historical wind data is crucial to evaluate the feasibility of wind development. Monsoon winds and the sea-land breeze system impact wind patterns in coastal parts of Nigeria [9]. Wind speeds and directions change with the seasons, and there are times of year when it is best to harness wind power. Wind speeds in coastal regions are enough for utility-scale wind farms, according to historical data gathered from weather stations and satellite observations, to assess regional and temporal changes and the effect of climate change on these patterns [10], [11], however, in-depth investigations are necessary. Therefore, this understanding is crucial, especially in the coastal parts of Nigeria, where wind energy has the potential to be quite big. Building predictive models for energy management, designing energy infrastructure, and making strategic decisions about where to put turbines all rely on it. However, the efficiency and reliability of wind energy systems are seriously jeopardised by the climate-related unpredictability of wind patterns [8]. This scenario emphasises the need to study climate change's effects on wind energy and create adaptable strategies to keep power running in the future.

Adaptive solutions that could strengthen future energy sustainability are outlined in this research, which aims to critically examine the influence of climate change on wind energy potential in coastal Nigeria. It aims to fill the information vacuum about the particular effects of climate change on wind power by illuminating how certain areas can see their energy paradigm rethought due to climatic shifts. This research delves into the flexibility and susceptibility of wind energy production by analysing existing and projected wind patterns under different climate change scenarios. It seeks to navigate beyond general assessments of renewable energy viability or the overarching effects of climate change on renewable resources. Instead, it zooms into the nuanced implications of climate variability on wind patterns and energy production within Nigeria's coastal regions. In propounding adaptive strategies, this study conscientiously considers the unique socio-economic and environmental contexts of the coastal states, enriching the discourse on renewable energy sustainability amidst climatic adversities. The distinctiveness of this research lies in its focused examination of how climate change influences wind energy potential in Nigeria's coastal states and its advocacy for bespoke adaptive strategies. This methodology deepens the comprehension of the interconnections between climate change and wind energy. It furnishes pragmatic solutions to enhance the resilience and sustainability of wind energy systems against the backdrop of ongoing climatic transformations.

CLIMATE CHANGE AND WIND PATTERNS

A. Scientific Basis of Climate Change Affecting Wind Speeds and Patterns

Wind energy as a renewable energy has been noted to be one of the primary sources of clean energy production using wind turbines. It is one of the viable options of energy generation fronted to be a solution to climate change currently ravaging the world's ecosystem. Offshore wind turbines have been identified as one of the drivers to achieve the targeted 11TW of power generation anticipated from wind energy for 2030 ahead of COP28 [12]. However, this potential solution is facing threats from climate change's effects. Future variations in the flow of wind energy, namely wind power ramps caused by sudden variations in wind speed, can potentially affect the supply and integration of wind power into the grid [13].

The world's oceans are anticipated to be affected by climate change through wind speed and wave height alterations [14]. These alterations are anticipated as an increase in wave height in some regions and a decrease in others. The decrease in wave height culminates in 25.8% of global oceans such as Mediterranean Sea, the North Sea, the Northern Atlantic Ocean, and the Indian Ocean [15] [16] [17] [14] with extreme reduction in wind speed, period and height anticipated in the North Sea and Indian Ocean under the Representative Concentration Pathway (RCP) 8.5 scenario [17] [18]. A simulation study up to the year 2100 [19] found that this change with a significant decrease in wind resources is more evident in the mid-latitudes of the Northern Hemisphere. In contrast, other studies within the research community opined that there is a high uncertainty of changes in wind speed patterns. [20] [21]. However, the climate models used in the studies showed substantial discrepancies. In most studies, it is believed that climate change affects wind speed and patterns. Aside from wind speed and patterns, climate change impacts the performance of offshore wind infrastructures by altering many elements such as temperature, wind direction, sea level rise, icing on wind turbine blades, air density, wind turbulence, and current velocity [22].

B. Review of Studies on Climate Change Impacts on Wind Energy Globally

Given its global impacts and dimensions, climate change is a significant subject that the global community is concerned about [23]. This has been followed up by research efforts to study its national, regional, and global impacts. In the United Kingdom (UK) and its exclusive economic zone (EEZ), the northern regions, particularly the Scottish Islands and North Atlantic, have notably higher wind speeds than the southern parts [24]. The offshore and coastal regions experience more winds than the inland areas due to topography and thermal properties that determine pressure differences. The UK's mid-latitude position results in seasonal variations that affect wind resources by altering the delivery and redistribution of energy [24]. The average wind speeds in winter are 50% greater than in summer due to the increasing temperature gradient. Specifically, the average wind speed in winter is 9.2 m/s compared to 6.2 m/s in summer [25]. However, the research found that global warming culminating in weaker wind in the Northern Hemisphere could result in a 2% reduction in average wind farm outputs [26].

The European continent has, in the past, experienced various side effects, events, and disasters due to climate change, even up to 2013. Such examples include the heat waves of 2003 and 2010, cold waves of 2005-2006, and vast floods of 2002 and 2013, which have resulted in the loss of billions of Euros in damages and economic aftermaths and, most devastating, fatalities [27] [28] [29] [30]. Despite the losses generated by these devastating events, high winds frequently bring the most economic damage to Europe [31]. The challenge with wind speed changes is more evident due to the anticipated rise of extreme winds across northern, central, and southern Europe, suggesting a higher frequency of such events [31]. Using the Intergovernmental Panel on Climate Change, IPCC future climate projection from the CMIIP5 project, the Baltic Sea may see a rise in wind energy resources in the future for Europe, while in Southern Europe, future wind energy resources may decline [32]. This is due to changes in wind energy density.

In the United States of America, based on the RCP 8.5 climate models study indicate that coastal areas may see a 5–10% rise in 10 m wind speed per century but a 5–10% decrease in summertime wind speed [33]. An increase in wind speeds between 0.1 and 0.2 m/s by the 2040s is projected in the Great Plains, Northern Great Lakes Region, and Southwest US (located southwest of the Rocky Mountains). The Great Plains Region and the Southwestern US will have an average rise in wind speed of 0 to 0.1 m/s in the 2090s. Nevertheless, summertime winds may lessen in several US coastal regions [34]. Other studies also showed that certain areas of Kansas, Oklahoma, and northern Texas are anticipated to have an increased wind energy potential of 2%. In Africa, particularly in the southern part, the long-term mean wind speed median by 2050 is predicted to be near zero due to climate change [35]. For the Western African region, a simulation study based on current data suggests there is an anticipated decrease in energy production of up to 12% between (2021-2050), whereas power production is projected to increase by around 24-30% throughout most regions in between (2071-2100) [36].

C. Specifics of Climate Change Impacts on Nigeria’s Coastal States

Nigeria, as a country, is experiencing the effects of climate change. The obvious evidence of climate change in Nigeria is the escalation in temperature and the variations in precipitation patterns, with coastal regions reporting a rise in rainfall and inland areas undergoing a decline [37]. These occurrences are also apparent in drought, desertification, rising sea levels, erosion, floods, thunderstorms, landslides, land degradation, more frequent and severe weather events, and decreasing biodiversity. As an agricultural nation, Nigeria has felt the impact of climate change in the reduction of crop yields and destruction of farmlands because of flooding and drought as is the case in many African countries [38]. Flooding in coastal states of Nigeria has been attributed to climate change effects by many studies [39] [40], [41]. These floodings cause damages and loss of properties, including infrastructures. Fig. 1 is a Nigeria map that shows the areas prone to flooding as noted by [42].

Furthermore, satellite imagery from VIIRS data and Landsat data were used for a bolder observation, as shown in Fig 2. An increase in flooding was observed in coastal regions due to heavy rainfalls and a rise in water levels. Indeed, coastal regions in Nigeria has experienced the effects of the adversity of climate change, and thus, intervention requires taking proactive steps.

Fig. 1 Regions prone to flooding in Nigeria [42].

Fig. 2 River Niger as of June 12, 2022 and October 2, 2022 (before and after flooding) [43].

With respect to wind potentials in the coastal regions of Nigeria, a study by [44] on time series assessment for power generation in Nigeria, it was concluded that the onshore locations in the Southern part of the country showed a relatively low wind potential for power generation, a direct contrast for offshore locations of the same location as studies show a higher wind turbine power output [44]. Lagos coast, Cross river, and Uyo showed the greatest wind power output amongst the coastal states with power output of 215kW, 194kW, and 188kW respectively at 50m of turbine hub height, making good potential locations. In another study by [45] on coastal region in Nigeria using Weibull, lognormal and normal probability density functions, analysis found that Lagos coastal region shows higher power output, and it is good potential sites for wind farm. This is in consistency with the assertions of [44]. However, coastal states such Ondo, Edo, Bayelsa, Delta, Calabar and

Rivers are deemed a location not good enough to site wind turbines because of projected wind low mean wind speed, and mean power density resulting to decreasing power output, because of climate change [44] [46].

FUTURE PROJECTIONS

A. Modeling and Prediction of Future Wind Patterns Under Climate Change Scenarios.

Evaluating the potential of wind energy requires precise modelling and prediction of future wind patterns under climate change scenarios. For sustainable energy planning, it is essential to understand the consequences of climate change on wind behaviour, since this has a direct bearing on atmospheric dynamics. Coastal states in Nigeria, for example, are very vulnerable to weather changes owing to their position, and climate change is already causing changes in wind patterns that can have a major impact on wind farms' ability to generate electricity [47]. Both Global and Regional Climate Models (GCMs and RCMs, respectively) are crucial for predicting wind conditions in the future. The impact of shifting weather patterns on local and regional wind speeds and directions can be better understood with the use of these models. Notable models, like the Hadley Centre's and the IPCC AR5 (including CMIP5), provide comprehensive simulations of wind patterns under different greenhouse gas trajectories [48]. Predicting changes to wind patterns and how they can affect energy infrastructure relies heavily on these models.

Expert wind prediction methods are used to transform the results of climate models into realistic predictions of wind speeds. Utilising Computational Fluid Dynamics (CFD), WindSim and the Wind Atlas Analysis and Application Program (WAsP) are capable of forecasting future wind potentials by combining data from climate models with topography and atmospheric information [49]. In order to maximise energy output, these models are essential for optimising the sites and designs of wind farms. To comprehend the consequences of alternative climatic trajectories, scenario analysis is essential. To help evaluate the robustness of wind generating projects in different environmental contexts, Representative Concentration Pathways (RCPs) like RCP8.5 and RCP4.5 provide different predictions depending on concentration levels of greenhouse gases. Wind power has the potential to play a significant role in Nigeria's future energy infrastructure, therefore these scenarios should take that into consideration [50].

To get the most out of the models, one need reliable weather data like wind speed, air density, and temperature. Most of the time, this information comes from weather stations on the ground, satellite observations, and reanalyses of the atmosphere. Gilbert et al., [51] found that the accuracy of wind forecasts is significantly impacted by the availability and resolution of this data. There are still a number of obstacles to overcome, even if modelling methods have improved. Data scarcity makes thorough regional analysis more difficult in developing countries like Nigeria's. Another major obstacle to accurate forecasts is the need for local calibration and the inherent uncertainty in the models. Data gathering, model improvement, and ongoing validation against observed data must be coordinated to overcome these obstacles [52].

B. Potential Changes in Wind Energy Production Capabilities

The coastal regions of Nigeria have long stretches of coastline that make them ideal locations for wind farms, but thus yet, very little has been done to tap into this potential. Studies show there is a lot of unrealised potential for wind power, but recent evaluations show that only a small amount of it is really built. This is especially true in states like Lagos, where the wind speeds are high enough to generate a lot of electricity [53]. Understanding the growth potential and implications of climate-induced changes in wind patterns requires acknowledging this baseline. Wind speeds and, by extension, the capacity to generate wind power, are expected to vary in the future due to changes in wind patterns caused by climate change. According to Matthew et al. [47], an increase in the density of wind power along the coasts of Nigeria might be caused by stronger trade winds in some climatic scenarios. For example, under the best-case scenario (RCP8.5), wind speeds might increase by 10% by 2050, leading to a 20% increase in wind power density. Because they affect choices about the location and size of wind farm expansions, these predictions are vital for planning purposes because they connect directly with the power generating capacity of wind turbines.

These developments have major ramifications for the economy. As wind speeds increase, they have the potential to lower the LCOE, which would make wind power a more attractive alternative in the energy market. To compensate for the unpredictability of the power supply brought on by shifting wind patterns, further investments in grid integration technology and energy storage can be required. For new or enlarged wind energy projects to be financially viable under future climatic circumstances, cost-benefit evaluations must take these considerations into account [54]. It can be necessary to implement new turbine technology in order to adjust to shifting wind conditions. It can be essential to use turbines designed for greater wind speeds or to use designs that are more resilient and can handle more unpredictability. As a result of climate change, adaptive management techniques can be necessary to optimise efficiency and resilience; these can include variable speed operations or dynamic turbine orientation [55].

Strong legislative actions are essential to help the wind energy industry adjust to these developments. A more stable wind power supply can be better managed with improved grid integration policies, such as more accurate forecasting tools and funding for smart grid technology. Further, the sector's development and sustainability might be expedited by the implementation of subsidies or financial incentives for the use of modern wind technology. Additionally, policies that support the advancement of wind energy technology that are resistant to climate change will provide reliable energy supply in the long run [56]. Although these ideas highlight the possibilities and obstacles of wind energy growth in the face of changing climate, it is crucial to maintain a critical mindset and take into account other viewpoints. Whether wind energy can become a sustainable part of Nigeria's energy future depends on how technology progress, economic factors, and regulatory frameworks interact with one another.

C. Spatial and Temporal Variations in Wind Energy Potential

Changing wind patterns brought about by climate change are going to drastically alter the geographical distribution of wind energy potential in the coastal regions of Nigeria. Areas with modest wind speeds now can witness increases in wind velocity, according to research [57], making them potential locations for wind energy installations. Wind farm construction and infrastructure investment objectives will need to be reevaluated in light of this transition. By using GIS and remote sensing technology, these changes can be effectively adapted to. As circumstances change, these technologies let us see wind resource data visually across time, which helps us find new wind energy hotspots [58]. Planners can generate up-to-date, detailed maps by combining information from sensors on the ground with data collected from satellites. When planning the placement of new wind farms and adjusting energy system architecture to accommodate increased power flows, these maps are essential.

When preparing for the operational stages of wind energy generation, seasonal changes in wind patterns are crucial. Na et al. [59] found that the wind power availability in coastal areas of Nigeria is greatly enhanced during particular months when the winds are greater owing to seasonal climatic changes, such as the West African Monsoon. To maintain a steady supply of energy, it is necessary to plan ahead for times of low wind speeds and adjust for them using grid integration and energy storage options. Evaluating the impact of predicted climate change scenarios on wind patterns across decades is also important for understanding the long-term viability of wind generating installations. National energy sustainability targets can be more difficult to attain if certain areas have a net gain in wind energy potential while others experience declines [60]. In order to keep up with these developments and adjust energy policies appropriately, it is crucial to continuously monitor and update models.

Comprehensive wind resource evaluations, like the one carried out by Kenya's Lake Turkana Wind Power Project, take into account both space and time. This project has shown to be resilient in the face of varying climates, and it is now being used as an example for other large-scale renewable energy projects in Africa [61]. The Alta Wind Energy Centre in California, USA, also made use of cutting-edge GIS and remote sensing data to optimise grid integration and turbine location, taking into consideration both the present and future changes in wind patterns caused by climate change [62].

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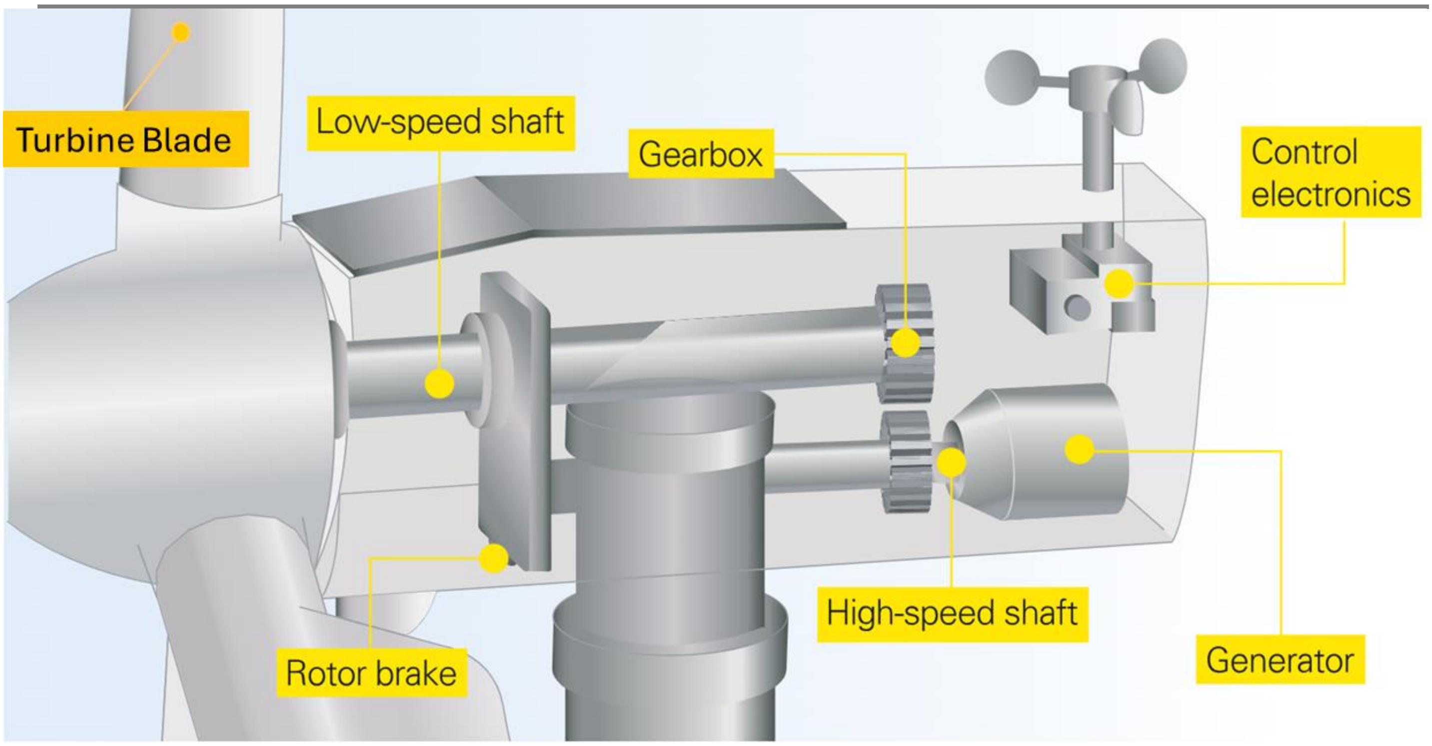

Fig 3 Turbine design (Adapted from [63])

This method proved the value of careful spatial and temporal planning by making sure the project could still be carried out in the event of different future circumstances. These cases demonstrate why wind energy project developers must consider both space and time when making decisions. Optimising wind energy potential and developing robust infrastructure to satisfy future energy needs can be achieved by Nigeria via the use of modern technology and continual monitoring.

ADAPTIVE STRATEGIES FOR WIND ENERGY INFRASTRUCTURE

A. Technological Adaptations to Optimize Efficiency Under Changing Wind Conditions

The preceding sections establish that wind patterns are changing due to varying geographic features and overall climate change action. Therefore, it is necessary to adapt the technology to these changes to optimize the reliability efficiency and longevity of infrastructures already in place and those expected to be installed for future activities. Typical examples are the turbines. Turbines play significant roles in power generation, and most turbines are activated by wind [63]. Turbines, as seen in Fig 3**,** are designed to generate as much power from wind energy; however, the traditional fixed-pitch blades limit their efficiency in regions with high and variable wind speeds [64], [65]. Coastal regions often experience high variable wind speeds. Technological advancements have introduced variable pitch blades, which can be adjusted at angles to fit the wind direction and speed. This accommodates broader ranges of wind speeds, reduces the risk of damage, and increases energy output. Modifying the turbine blade design is a typical adaptation to energy infrastructures in changing environments. Also, wind speed increases with altitude, making longer blades more effective in capturing winds at higher elevations [66].

These installations are often seen in offshore wind farms, like the Great Plains of the United States [67], [68]. Furthermore, turbines' structural design and materials are improved to fit the larger wind, cyclic stress, and toughness. Carbon fibre composites are improved materials for blades capable of withstanding stresses to minimize structural failure [69], [70]. In recent years, technology has made using sensors (adapted to the control electronics) very popular in engineering applications, as they enable the real-time control of systems. Wind turbines also adopt these strategies in altering blade pitch, rotor speeds, and operations in the gearbox, as seen in Fig 3, especially in coastal regions where sudden changes in wind direction and speed are expected [63], [71], [72].

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Integrating the grids to accommodate renewable energy in Nigeria is also a technological challenge [73]. To manage these in recent years, smart grid integration has been deployed in the integration of distributed energy resources, grid resilience, and real-time monitoring and control [73], [74], [75]. Areas with smart grid technologies were easily restored after Hurricane Sandy [76], [77]. This is a major benefit compared to traditional energy source integration systems. In Smart grids, sensors and automated controls are installed to respond to grid disturbances. The Tennessee Valley Authority also adopts a smart grid system, providing them with real-time data and management of the energy supply [78], [79]. Germany's integration of high levels of wind energy into its grid has also shown how smart technologies can help balance supply and demand in changing environments [80], [81]. Adaptive strategies revolutionize wind energy generation as they offer significant benefits in optimizing production; however, they also face challenges of increased design complexity and cost. Also, cybersecurity risk, infrastructural upgrades, and regulatory hurdles are challenges that further studies can aid in minimizing.

B. Policy and Planning Strategies

In Nigeria, funding for renewable energy projects is low [82], [83], making it challenging since climate change actions are not limited to one continent, country, or region. Curbing the difficulties posed by climate change requires a collective effort by every country; hence, this study, in an attempt to explore the potentials of wind energy, identifies investments aimed at research and development in wind energy and incorporating climate projections into energy planning within Nigerian coastal region as a means towards tacking climate change actions. Some methods of promoting investments are public funding in energy research, public-private partnerships, incentivizing breakthroughs through patents, tax reduction, subsidies, and support for academic and research institutions [84], [85]. Funding research stages by Government or private bodies reduces the risks the researchers or scientists are scared of taking, encouraging them to explore wider research areas under controlled conditions. In integrating climate projections into energy planning, developers need to conduct risk assessments and adaptation plans with short- and long-term scenarios that will aid the reinforcement of wind energy infrastructures, as discussed earlier, and the energy mix.

Furthermore, these projections are not void of stakeholder engagement and public participation since the risk of climate change affects the communities where such infrastructure will be installed, and the energy from wind farms may be substituted for alternative energy sources that are less environmentally friendly. Indigenous knowledge of the locals is also very necessary in adaptative strategies. This supports co-development approaches or local participation, giving qualitative context to present technologies used in wind energy generation and unique designs tailored to the environment where installations will be made [86], [87]. In general, navigating the energy transition and utilizing opportunities for renewable energies such as wind energy, which this study explores, requires research and development and critical integrated planning and strategies that create better platforms for inventions and improvements.

CASE STUDIES AND COMPARATIVE ANALYSIS

A. Examples of Adaptive Strategies in Similar Climatic Regions

An effective response to the effects of climate change on wind energy potential can be better understood by looking at adaptation techniques in areas with comparable climatic conditions to the coastal states of Nigeria. Nigeria can learn a lot about wind energy by studying how other locations deal with climate change-related wind pattern changes and unpredictability. There have been major developments to strengthen the wind energy industry in Brazil's Northeast Region, which has a long coastline and a tropical environment similar to that of the coastal regions of Nigeria. The area has fully embraced the use of dynamic turbine technology in conjunction with high-resolution weather forecasting systems. This setup is designed to adapt to different wind speeds and directions, making it easier to maximise energy collection and improve farm performance as a whole. In addition to increasing energy production, this method decreases maintenance expenses by reducing component wear and tear on turbines [88]. Moving eastward, monsoonal climates like those in coastal Nigeria can be found in southern India, namely in the states of Karnataka and Tamil Nadu. In this case, adaptive tactics have concentrated on managing the grid and integrating energy storage options to deal with the variations in the availability of wind power. Furthermore, these nations have played a crucial role in developing hybrid wind-solar systems. electricity supply stability and less dependence on a single energy source are two benefits of these systems that combine wind and solar electricity [89].

On the other hand, in Southern California, USA, efforts have been made to establish a regulatory and planning climate that is favourable to the adaption of wind energy. To ensure that wind turbines are located in areas with optimum long-term wind availability, the state has enacted zoning regulations that are influenced by climate models for the long term. According to Azevêdo et al., [90], wind energy projects can be economically viable and sustainably run using this preventative approach to regulatory design, which protects investments from the possibility of future lower wind speeds. These case studies show that in order to respond to the climate change issues, it is necessary to implement strategic regulatory frameworks, embrace hybrid renewable systems, and integrate modern technical tools. These case studies show how Nigeria can strengthen its new wind energy industry to better withstand and harness the power of climate change. Nigeria can build a strong and sustainable wind energy future by studying the methods and accomplishments of other places and adapting them to its own climate and geography.

B. Lessons Learned and Applicability to Nigeria's Coastal States

In order to increase their wind power capacity in the midst of climate change, the coastal states of Nigeria might learn from the examples set by Brazil, southern India, and southern California. Wind farms in Brazil have become much more efficient when cutting-edge weather forecasting techniques were used. Optimal power generation and successful management of grid integration depend on accurate wind predictions, which Nigeria can achieve by using comparable technologies [91]. To maximise energy production and minimise operational hazards, such forecasting systems might allow for more accurate real-time modifications to turbine operations, adjusting to abrupt changes in wind speed and direction. The advantages of combining wind with other renewable energy sources, such solar electricity, are further shown by the successful hybrid renewable systems in southern India. Lolla et al., [92] found that this combination helps reduce the effects of seasonal fluctuation, making the energy supply more regular and predictable. Hybrid systems like this have the potential to improve power system stability in Nigeria by ensuring a more consistent energy supply all year round, thanks to the country's abundant wind and solar resources. Another important thing that Nigeria can learn from California is how they deal with wind power, which is all about proactive zoning and regulations. To make sure wind energy infrastructure projects in Nigeria are sustainable financially and ecologically, the country should include climate change predictions into its planning and regulatory framework [47]. To encourage developers and investors to commit for the long haul, these visionary policies might aid in the discovery and protection of regions with great wind energy potential. Education and involvement in the community are also crucial. It is critical to have communication plans in place that inform stakeholders and local populations about renewable energy's advantages and the need for adaptable solutions. The long-term viability of wind farms depends on these kinds of initiatives gaining more public support.

DISCUSSION

A. Implications of Findings for Wind Energy Sustainability

Renewable energy sources like wind power are crucial for lowering emissions of greenhouse gases and reliance on fossil fuels [93]. Production costs are only one aspect of wind energy's economic viability; other considerations include market forces, government regulations, and subsidies. Switching to wind power has far-reaching sustainability consequences. Vargas et al. [94] found that investing in wind energy technology can significantly decrease greenhouse gas emissions, since increasing energy consumption reduces $CO2$ emissions in nations with lower economic complexity. Because it is renewable and clean, wind power doesn't harm the environment as fossil fuels do. It helps reduce air pollution and the health concerns linked with it while also generating electricity without creating carbon dioxide when used. Wind power, which is both renewable and infinite, eliminates the environmental risks and pollution associated with fossil fuels since it does not involve the extraction, transportation, or management of fuel. However, factors like as location, building methods, and competing land use determine the environmental implications of wind energy deployment on a site-by-site basis. The introduction of wind power in ecologically fragile regions can need comprehensive EIAs, in contrast to the usually negligible ecological implications of installations in industrialised areas, which are mostly limited to aesthetic concerns. Wind energy's environmental and economic advantages are complex and location-dependent, highlighting the need of weighing the pros and cons for long-term energy sustainability [95].

Renewable energy strategies that really work will take wind power's effects on the environment into account. It is important to address any impacts on human health, local climate, land use, marine ecosystems, and animals as part of mitigation efforts. There has to be continuous study, optimisation, and the use of appropriate design and operational approaches to guarantee environmental sustainability as wind energy grows, because there can be more noticeable environmental consequences than before [96]. In order to create policies that encourage the long-term expansion of wind power, it is essential to have a firm grasp of these consequences. To fully realise wind energy's potential in attaining sustainability objectives in the long run, policymakers should weigh its advantages against any possible negative impacts on the environment.

B. Challenges in Adapting Wind Energy Infrastructure to Climate Change

In order to keep wind power a reliable and long-term part of the world's energy mix, it is essential to adapt wind energy infrastructure to the effects of climate change. Climate change is causing changes in wind patterns, which is a big problem. As wind farms are usually constructed using past wind data, these alterations might impact the reliability and consistency of wind power production. Therefore, in order to keep efficiency and output constant, site selection, turbine design, and grid integration techniques must be reevaluated in light of changes in wind patterns [97]. Hurricanes, cyclones, and severe storms are becoming more often, which makes it harder to modify wind energy equipment. Wind turbines need to be sturdy enough to endure these kinds of storms without being severely damaged. For wind energy projects to last and be safe, structural designs need to be improved, better materials used, and better maintenance procedures put in place [98].

Another major concern is the potential impact of rising sea levels, which is especially true for offshore wind farms situated near coastlines. The foundations and transmission infrastructure of offshore wind turbines are under risk from rising sea levels. Turbine platforms can be raised, foundations can be reinforced, and coastline protection measures can be put in place to ensure the safety of these sites as a result of this phenomena [99]. Wind turbine efficiency and performance are also affected by heatwaves and cold snaps. Overheating components is possible in very hot environments, whereas lubricants, materials, and electrical systems are vulnerable to damage in very cold environments. As a result, wind turbine designs need to be refined to endure a wider spectrum of temperatures, guaranteeing dependable performance in diverse regions [100].

Wind energy has environmental implications such habitat loss, animal relocation, and altered biodiversity; these impacts can be worsened by climate change. Efforts to restore habitats, create new technology that lessen negative impacts on ecosystems, and conduct more thorough environmental assessments are all necessary to minimise these consequences [101]. There are many legislative and regulatory frameworks that must be navigated in order to adapt wind energy infrastructure to climate change. Wind energy solutions that are robust and adaptable to climate change should be encouraged by governments and regulatory bodies via the implementation of updated standards, guidelines, and incentives. To coordinate adaptation activities across areas and solve transboundary challenges, international collaboration is necessary [94]. Because of these difficulties, adapting wind energy infrastructure to the changing effects of climate change requires a comprehensive strategy. For wind energy systems to grow in a sustainable and resilient way, this strategy has to include new technologies, strong legislative frameworks, and global cooperation.

C. Opportunities for Enhancing Wind Energy Resilience

Wind energy infrastructure resilience enhancement presents a multi-faceted opportunity to optimise performance and sustainability while mitigating risks associated with climate change and other problems. This necessitates new forms of government, community involvement, technological development, and environmental consciousness. By seizing these possibilities, stakeholders can greatly strengthen the robustness and resilience of wind energy. In order to make wind energy more resilient, technological innovation is crucial. Turbines that can endure severe weather like lightning, ice, and strong winds will be possible with the development of more resilient materials and flexible designs. Turbine blades can be made more resilient to storm damage because to developments in materials science that make them both stronger and more flexible. Optimising turbine performance and lifetime is possible using smart technologies and predictive maintenance systems. These systems use data analytics to anticipate and treat potential faults before they become worse [102]. To make wind energy more resilient, we need to integrate the grid better and increase our energy storage capacity. Barelli et al. [89] found that wind energy can be made more dispatchable and dependable by using energy storage technologies like battery storage. This would solve the problem of intermittent energy generation. In addition, smart grid development and other grid modernisation initiatives can control the intermittent and dispersed character of renewable energy sources, making for a far more reliable and efficient power infrastructure. Improving the wind energy infrastructure's resilience is mostly dependent on policy frameworks and financial incentives. Policies can be put in place by governments and regulatory agencies to promote the study and creation of wind energy technologies that are more robust. Subsidies, tax credits, and grants are monetary incentives that can reduce the out-of-pocket expense of implementing new technology and improving existing infrastructure. Rapid adoption of resilience-enhancing measures can be achieved by policies that make it simpler to finance renewable energy projects.

CONCLUSION

This study emphasises the substantial potential of wind energy as a renewable and sustainable energy source in the coastal regions of Nigeria, in view of the ever-evolving climate change issues. The comprehensive analysis of past wind data, prospective predictions, and case studies from regions with analogous climatic conditions provides a comprehensive understanding of the impact of climate change on the potential for wind energy. This research also identifies adaptive strategies that can enhance the sustainability and resilience of wind energy infrastructure. The study discovered that there are substantial opportunities to mitigate these impacts through the implementation of new technology, improved policies, and meticulous planning, despite the fact that wind energy development is confronted with climate change-related threats, including altered wind patterns, more frequent and severe weather events, and rising sea levels. Adaptive solutions are essential to ensure an efficient and reliable energy supply and maximise wind power generation. These consist of the integration of smart grid technology, enhanced weather forecasting tools, and hybrid renewable systems. Nigeria has the potential to gain valuable insights from the successes and failures of other regions, including the Northeast of Brazil, Southern India, and Southern California. These regions have demonstrated the advantages of integrating high-resolution weather forecasts, regulatory frameworks, and dynamic turbine technology, which are informed by long-term climate models. Nigeria can achieve greater efficiency in utilising its substantial wind energy potential and enhance its wind energy industry's resilience to climate change by adopting this approach. For wind energy projects to be socially acceptable and successful in the long run, stakeholder and community participation is crucial. As a nation, Nigeria can combat climate change and reap economic, cultural, and environmental advantages by making smart investments in wind power. Nigeria has the potential to lessen its impact on the climate change challenge by using its long coastline and strong winds to produce less greenhouse gas emissions. Improving climate models, developing better ways to gather and analyse data, and coming up with novel turbine designs and materials that can handle the problems caused by a changing climate should be the focus of future study. Promoting wind energy and positioning the coastal states of Nigeria as leaders in developing environmentally friendly energy would need close cooperation between the public sector, industry, and institutions. This study's findings provide the groundwork for an all-encompassing plan to develop the coastal states of Nigeria's wind power sector. In an era of climate uncertainty, it is imperative to implement a multifaceted approach to the development of a sustainable wind energy infrastructure that can withstand and surpass Nigeria's anticipated energy requirements. Technical, legislative, and community-based components should comprise this strategy. Nigeria has the potential to establish a more sustainable and greener energy future by collaborating and executing a well-planned strategy. This would enable the nation to contribute to the global climate change initiative, improve energy security, and stimulate economic growth.

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