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THE DEVELOPMENT OF WIND ENERGY IN BRAZIL: ADVANCES, CHALLENGES AND IMPACTS OF WIND FARMS IN THE NATIONAL CONTEXT AND FUTURE PROSPECTS

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Abstract: The development of wind energy in Brazil has emerged as one of the country's main sources of renewable energy, reflecting a growing commitment to sustainability and diversification of the energy matrix. However, the growth of wind energy in Brazil also faces challenges that need to be addressed to ensure its long-term sustainability. In this context, it is important to highlight that wind energy is not only an energy alternative, but also an opportunity for Brazil to position itself as a leader in the global energy transition. The aim of this paper is to analyze the development of wind energy in Brazil, highlighting the progress, challenges and impacts of wind farms in the national context, as well as the future prospects for this renewable energy source. It concludes that the development of wind energy in Brazil has advanced significantly in recent decades, becoming one of the country's main sources of renewable energy. This growth not only contributes to the diversification of the national energy matrix, but also promotes sustainability and the reduction of greenhouse gas emissions. Despite this progress, the sector faces challenges that need to be overcome to ensure its continued expansion. Regulatory issues, such as the need for more robust public policies and financial incentives, still represent obstacles for investors and wind project developers. Furthermore, the installation of wind farms can stimulate the regional economy, creating jobs and improving local infrastructure. Finally, the future prospects for wind energy in Brazil are promising, with the potential for expansion into new areas and the implementation of innovative technologies that increase generation efficiency. The development of energy storage systems and integration with other renewable sources, such as solar, can provide a more stable and reliable energy supply.

Keywords: Wind energy. Wind farms. Progress. Challenges. Future prospects.

INTRODUCTION

The development of wind energy in Brazil has become one of the country's main sources of renewable energy, reflecting a growing commitment to sustainability and diversification of the energy matrix. Since the 2000s, Brazil has invested significantly in the construction of wind farms, especially in the Northeast region, which has considerable wind potential due to its favorable climatic conditions. The expansion of wind energy not only contributes to reducing dependence on fossil sources, but also to reducing greenhouse gas emissions, in line with global targets to combat climate change.

However, the growth of wind energy in Brazil also faces challenges that need to be addressed to ensure its long-term sustainability. Among the main obstacles are the need for investment in infrastructure, the interconnection of the electricity grid and regulatory issues that can impact the development of new projects. In addition, it is essential to consider the social and environmental impacts associated with the installation of wind farms, which can affect local communities and ecosystems. Therefore, a balanced approach that takes into account both the economic and environmental benefits of wind energy and the possible repercussions for affected populations is essential.

In this context, it is important to note that wind energy is not only an energy alternative, but also an opportunity for Brazil to position itself as a leader in the global energy transition. With a potential that is still underutilized, the country can further exploit its wind capacities by promoting technological innovation and attracting investment. Understanding the progress, challenges and impacts of wind farms in Brazil is essential for drawing up guidelines to ensure the responsible and effective expansion of this energy source, benefiting the economy and society in a sustainable way.

The aim of this paper is to analyze the development of wind energy in Brazil, highlighting the progress, challenges and impacts of wind farms in the national context, as well as the future prospects for this renewable energy source.

In this context, the choice to analyze the development of wind energy in Brazil is justified by the growing importance of this renewable energy source on the national and global energy scene. With the growing demand for sustainable solutions, wind energy presents itself as a viable alternative for diversifying the energy matrix, reducing dependence on fossil fuels and helping to mitigate climate change. In addition, Brazil has significant wind potential, especially in the Northeast region, which can still be exploited. Understanding the advances, challenges and impacts of wind energy is essential to promoting an energy transition that benefits not only the economy, but also society and the environment.

Another important aspect is the role of wind energy in regional economic development and job creation. The installation of wind farms not only boosts the generation of clean energy, but also creates job opportunities in local communities, helping to strengthen the regional economy. However, this expansion must be carried out responsibly, taking into account the associated social and environmental impacts. Therefore, this study is crucial to subsidize public policies and business practices that promote a sustainable and balanced development of wind energy in Brazil, ensuring that the benefits are widely distributed among all stakeholders.

METHODOLOGY

The methodology of this study is based on bibliographical research, which is characterized by the critical and systematic analysis of existing academic production on a given topic. According to Gil (2010), bibliographical research is an approach that allows the researcher to get to know the state of the art on the subject in question, providing a solid theoretical basis for discussion. This methodology is especially useful for understanding the advances, challenges and impacts of wind energy in Brazil, since it allows access to and synthesis of different perspectives and information available in the literature.

To carry out the bibliographical research, recognized academic databases such as Scielo and Google Scholar were used. The keywords used in the searches included “wind energy in Brazil”, “development of wind farms”, “impacts of wind energy”, “challenges of wind energy” and “sustainability of wind energy”. These keywords were chosen in order to cover a wide range of publications related to the topic, allowing for a more complete and diverse analysis.

The time frame of the research covered the last 10 years, from 2014 to 2024, in order to ensure that the information collected is recent and relevant. The inclusion criteria consisted of articles, theses and dissertations that specifically addressed the development of wind energy in Brazil, publications in indexed journals, and official documents that discussed policies and regulations in the sector. On the other hand, materials that did not focus on the Brazilian context, publications from unreliable sources or without peer review, and documents that dealt with wind energy in a superficial or general way, without substantial critical analysis, were excluded. This approach ensured that the research was carried out rigorously and that the information collected was relevant and of high quality.

THEORETICAL DISCUSSION

HISTORY OF WIND ENERGY IN BRAZIL

Wind energy in Brazil has a history dating back to the beginning of the 20th century, although its effective development as a renewable energy source has only begun to gain prominence in the last two decades. At first, wind turbines were used experimentally and on a small scale, mainly in rural areas where electrification was still a challenge. Over the years, and especially since the 1990s, the country has seen a growing interest in alternative energy sources, driven by the need to diversify the energy matrix and the search for more sustainable solutions for electricity generation (SAMPAIO E BATISTA, 2021).

In 2001, Pinto et al. (2017) point out that Brazil experienced a significant energy crisis, which culminated in energy rationing. This scenario brought to light the urgency of exploring renewable energy sources, including wind power. The federal government implemented a series of policies and incentives to encourage investment in wind farms. During this period, the Renewable Energy Incentive Law was created, which established guidelines for the development and implementation of wind projects, as well as facilitating access to financing for new ventures. Since then, the country has seen an accelerated growth in the number of wind farms, especially in the Northeast and South, where climatic conditions have proved favorable to wind generation.

Since 2010, wind energy in Brazil has been consolidated as one of the main sources of renewable energy, with specific auctions being held to contract wind energy. Since 2013, Brazil has stood out as one of the world leaders in wind power generation, attracting significant investment from both national and international companies. In addition, the

country has joined the list of the world's top ten wind energy producers, with a growing installed capacity of over 20 GW. This growth has not only contributed to reducing dependence on fossil energy sources, but has also promoted economic benefits, such as job creation and the development of local technologies (CUNHA et al. 2019).

The success of wind energy in Brazil is also due to factors such as cooperation between the government and the private sector, which has made it possible to create a favorable environment for investment in renewable energy. However, challenges still remain, such as the need to improve transmission infrastructure and the integration of wind energy into the national energy matrix. As Brazil continues to exploit its wind potential, future prospects include not only increasing installed capacity, but also implementing new technologies and sustainable practices to ensure the sector's efficiency and competitiveness in the global market (PINTO et al. 2017).

TECHNOLOGICAL ADVANCES AND INNOVATION

In recent years, according to Coletta et al. (2022), technological advances and innovations in the wind energy sector have been fundamental to increasing the efficiency and competitiveness of wind farms around the world, including Brazil. The development of new wind turbine technologies, for example, has made it possible to generate energy in a variety of climatic conditions, increasing the viability of projects in regions previously considered unsuitable for the installation of wind farms. Modern turbines have longer and lighter blades, which allow them to capture a greater volume of wind and, consequently, increase energy production. In addition, the introduction of advanced control systems enables turbines to automatically adjust their angle in response to changes in wind speed, maximizing efficiency and operational safety.

Another relevant aspect of technological advances, according to Lopes et al. (2020), is the implementation of energy storage solutions and integration with smart grids. With the intermittency of wind generation, it is crucial to have systems that can store the energy generated during periods of high production for use during times of low generation. The development of high-capacity batteries and energy management systems has led to greater stability in the supply of wind energy, making it more reliable. Smart grids, meanwhile, are capable of optimizing the distribution of the energy generated, improving the response to consumer demands and minimizing losses. These innovations have contributed significantly to wind energy becoming a fundamental part of the energy matrix, offering a more sustainable alternative to traditional energy sources.

Innovations are not just restricted to the development of specific technologies for wind turbines, but also cover operating and maintenance practices. The use of drones and IoT (Internet of Things) sensors to monitor and inspect turbines, for example, allows companies to carry out predictive maintenance and avoid unexpected downtime, resulting in efficiency gains. Real-time data analysis, made possible by digital technologies, enables more precise management of operations, identifying patterns that can lead to continuous improvements. This digital transformation is revolutionizing the sector, allowing companies to become more competitive and agile in a rapidly evolving market (ARAÚJO E GOMES, 2022).

Furthermore, Tinoco (2021) points out that collaboration between research institutions, universities and companies in the sector has been essential for the development of new technological solutions. Exchanging knowledge and carrying out joint projects has accelerated innovation and the improvement of existing technologies. Initiatives aimed

at training skilled labor and professional qualification have also been key to ensuring that professionals in the sector are prepared to deal with the new technologies and challenges that arise.

The impact of these innovations is evident not only in the increase in wind power generation capacity, but also in the reduction in production costs. According to Araújo and Gomes (2022), the cost of wind energy has fallen significantly in recent years, making it one of the most competitive energy sources on the market. This cost reduction is driven by improved turbine efficiency, economies of scale due to increased production and the development of cheaper technologies. As a result, wind energy is becoming increasingly accessible, not only in developed countries, but also in emerging markets such as Brazil, which has great potential for expansion.

As the wind energy sector advances, it is crucial that countries continue to invest in research and development, encouraging innovation and the adoption of new technologies. The future of wind energy is closely linked to the ability to adapt and evolve in the face of global demands for clean and sustainable energy. With the combination of advanced technologies, innovative practices and a collaborative environment, wind energy is well placed to play a central role in the transition to a more sustainable and resilient energy matrix (COLETTA et al. 2022).

CHALLENGES AND IMPACTS OF THE WIND SECTOR

Although the wind energy sector in Brazil has grown significantly in recent years, it faces a number of challenges that could impact its expansion and effectiveness. One of the main challenges is regulatory and financial issues. The incentive structure and legislation governing the installation and operation of wind farms are still complex and, in many

cases, insufficient to provide a favorable environment for investment. The lack of clarity in rules and regulations can lead to uncertainty for investors and developers, which can discourage new projects. In addition, dependence on government subsidies and incentives can pose a risk, especially in contexts of political and economic change. The financing available does not always meet the sector's demand, making it necessary to look for alternatives that guarantee the economic viability of ventures and ensure long-term sustainability (GORAYEB et al. 2019).

Another crucial aspect is the infrastructure and logistics required to install wind farms, according to Santestevan et al. (2021). The construction and operation of wind farms requires a robust infrastructure, including roads, specialized transport for turbines and heavy components, and connection to the electricity grid. Many regions with wind energy potential are remote, which makes access more difficult and increases installation costs. The need to interconnect with the existing electricity grid also represents a significant challenge, as transmission lines are often not adequately sized or positioned to support wind power generation. Improved infrastructure and logistical efficiency are therefore essential to facilitate the installation and operation of these projects, ensuring that the energy generated is properly distributed.

The impacts of wind farms on local communities and the environment also need to be considered. The installation of wind farms can have significant social repercussions on communities, both positive and negative. On the one hand, the creation of jobs during the construction and operation of the farms, as well as improvements to local infrastructure, can bring economic benefits. However, there are also concerns related to land occupation, displacement of communities and changes to the landscape, which can generate resis-

tance from local inhabitants. Interaction with the population is fundamental for projects to be well accepted and integrated into the social context, avoiding conflicts and promoting local development (NASCIMENTO et al. 2020).

Furthermore, according to Nascimento et al. (2020), the environmental effects of wind energy deserve attention. Although wind energy is a renewable energy source and considered less polluting, the construction of wind farms can impact local ecosystems and fauna, especially birds and bats. Studies have shown that the location and design of parks can mitigate these impacts, but it is crucial to carry out rigorous environmental impact assessments before installation. Continuous monitoring during and after the operation of parks is necessary to ensure environmental sustainability and reduce any adverse effects. Implementing conservation practices and integrating technologies that minimize impacts on wildlife are important measures for the sector to consider.

The sustainability of the wind sector is also linked to the need to ensure that the benefits of renewable energy are distributed equitably among the communities affected. To this end, it is essential to promote open dialogues between companies in the sector, the government and local communities, with a view to building partnerships that ensure that investments in wind energy bring direct benefits to residents. Incentives for community projects and initiatives that promote social inclusion are key to ensuring that the energy transition is fair and benefits everyone (GORAYEB et al. 2019).

As a result, the challenges facing the wind energy sector in Brazil, which include regulatory and financial issues, infrastructure and logistics, as well as social and environmental impacts, require an integrated and collaborative approach. Overcoming these challenges is essential if wind energy is to make a sig-

nificant contribution to the national energy matrix, promoting sustainable development and benefiting local communities. With proper planning, innovation and a commitment to sustainability, the wind energy sector can continue to grow and develop, becoming a key player in the transition to a cleaner and more renewable energy future (SANTESTEVAN et al. 2021).

FUTURE PROSPECTS FOR WIND ENERGY IN BRAZIL

According to Barra and Teixeira (2022), the future prospects for wind energy in Brazil are promising, with a number of potential new investment areas that could further boost the development of this sector. The country, rich in natural resources and with an extensive coastline, has significant potential for wind power generation, especially in the Northeast and South regions. Advances in technology and the growing demand for renewable energy sources have led investors to look for opportunities in previously unexplored areas, such as the interior of Brazil, where the expansion of electricity grids and improved infrastructure make it possible to install new wind farms. In addition, the diversification of energy sources and the search for sustainable solutions have attracted the interest of companies wishing to align themselves with social and environmental responsibility guidelines. Thus, new areas, such as generating wind energy in urban areas and installing turbines in offshore environments, are becoming viable, expanding the investment possibilities.

Technological innovations also play a crucial role in the future prospects of the wind sector in Brazil according to Santos and Araújo (2023). The development of more efficient turbines with greater generating capacity is constantly evolving, allowing wind farms to operate more effectively, even in variable wind conditions. Advanced

technologies, such as storing wind energy in batteries, are emerging as a promising solution for dealing with intermittent generation, ensuring that the energy generated is used optimally. Digitalization and automation are also proving to be key, enabling real-time monitoring and predictive maintenance of equipment, increasing the lifespan of wind farms and reducing operating costs. These innovations not only boost the sector's efficiency, but also promote a competitive environment, attracting new investments and stimulating growth.

In addition, Pinto and Santos (2019) point out that trends in the wind sector, driven by government policies and international agreements on climate change, indicate a strong inclination towards the expansion of renewable energy. With global commitments to reducing greenhouse gas emissions, wind energy is consolidating itself as a strategic solution for Brazil to achieve its sustainability goals. Growing awareness of the benefits of clean energy, along with available incentives and funding, encourages both companies and governments to invest in the sector. Partnerships between the public and private sectors are also a growing trend, resulting in more robust and sustainable projects. This synergy can accelerate the implementation of innovative technologies and strengthen the infrastructure needed for the expansion of wind energy, making Brazil a protagonist on the global renewable energy scene.

Finally, the future of wind energy in Brazil is full of opportunities, from new investment areas to technological innovations that promise to transform the sector. For Barra and Teixeira (2023), with the support of public policies and a growing commitment to sustainability, Brazil has the potential to become a leader in wind power generation in Latin America and beyond. The challenge will be to ensure that these opportunities are

seized in an equitable and sustainable way, benefiting not only the energy sector, but also local communities and the environment as a whole. The combination of abundant natural resources, technological innovation and a favorable regulatory environment could position wind power as one of the country's main energy sources in the coming years, contributing significantly to a diversified and sustainable energy matrix.

THE CONTRIBUTION OF WIND ENERGY TO SOCIETY

Wind energy plays a fundamental role in promoting sustainability and is one of the most promising renewable energy sources for reducing greenhouse gas (GHG) emissions. By generating electricity using the wind, wind farms make a significant contribution to reducing dependence on fossil fuels, which are the main contributors to GHG emissions, such as carbon dioxide (CO₂) and methane (CH₄). Replacing thermal power plants, which use coal or natural gas to produce energy, with wind farms results in a direct reduction in atmospheric pollution, helping to improve air quality and mitigate climate change. In various regions of Brazil, the expansion of wind energy has proved to be an effective alternative for diversifying the energy matrix, while generating positive impacts on the environment (PINTO, 2017).

Simas (2023) also points out that wind energy is aligned with the global climate goals established by international agreements, such as the Paris Agreement. This pact aims to limit the rise in global temperatures and promote actions to reduce greenhouse gas emissions worldwide. By committing to these goals, Brazil sees wind energy as an opportunity not only to meet international commitments, but also to lead the energy transition in a more sustainable direction. The adoption of public policies that encourage investment in wind

energy, such as energy auctions, subsidies and financing for renewable projects, strengthens the country's ability to achieve its climate goals and position itself as a model of sustainable development. The implementation of clean energy technologies is an effective strategy for accelerating the transition to a low-carbon economy, promoting not only energy security, but also social and economic justice.

Wind energy's contribution to sustainability goes beyond reducing greenhouse gas emissions, encompassing social and economic aspects that benefit local communities, according to Pinto (2017). Wind energy projects often involve investments in infrastructure, such as roads and electricity grids, which can benefit the local population. In addition, the creation of jobs in the construction and operation of wind farms promotes economic development in regions that often face socio-economic challenges. Raising awareness of the benefits of renewable energy can stimulate a culture of sustainability in communities, encouraging practices that respect the environment and promote the conservation of natural resources. In this way, wind energy not only contributes to reducing GHG emissions, but also strengthens communities' ability to adapt to climate change, promoting a more sustainable and resilient future for generations to come.

Furthermore, it is important to note that the growth of the wind sector in Brazil has encouraged research and the development of new technologies aimed at increasing the efficiency and economic viability of wind farms. Initiatives to improve energy storage and integrate renewable sources into the electricity grid are examples of how technological innovation is contributing to sustainability. The development of more efficient turbines and the implementation of real-time monitoring systems have made it possible to optimize energy generation and minimize the associated environmental impacts. Thus, wind ener-

gy not only contributes to sustainability in the present, but also paves the way for a more innovative and responsible energy future (VITOR, 2022).

Finally, the potential of wind energy extends even further when you consider the possibility of integrating it with other renewable energy sources, such as solar. According to Pinto (2017), this synergy can result in hybrid systems that make the most of climatic and geographical conditions, ensuring a more stable and efficient energy supply. The combination of different renewable energy sources not only diversifies the energy matrix, but also reduces costs and increases the resilience of communities in the face of adverse climatic events. Wind energy is therefore positioned as a strategic and viable solution to meet the energy and environmental challenges of the future, promoting sustainable development that benefits both the planet and the populations that depend on it.

CONCLUSIONS

The development of wind energy in Brazil has advanced significantly in recent decades, making it one of the country's main sources of renewable energy. With vast potential, especially in the Northeast and South, Brazil has stood out on the international stage, investing in technology and infrastructure to increase installed wind generation capacity. This growth not only contributes to the diversification of the national energy matrix, but also promotes sustainability and the reduction of greenhouse gas emissions. Wind energy is proving to be a viable and efficient alternative, reflecting the country's commitment to sustainable development and climate change mitigation.

Despite the progress made, the sector faces challenges that need to be overcome to ensure its continued expansion. Regulatory issues, such as the need for more robust public

policies and financial incentives, still represent obstacles for investors and wind project developers. In addition, the infrastructure and logistics for installing and operating wind farms require significant improvements, especially in remote areas where the winds are more favorable. These challenges require continuous dialogue between the public and private sectors in order to create a favorable environment for investment and technological innovation.

The impacts of wind farms go beyond energy generation, bringing social and economic benefits to local communities. The installation of wind farms can stimulate the regional economy, creating jobs and improving local infrastructure. However, it is crucial that projects are developed responsibly, taking into account the participation of affected communities and minimizing environmental impacts. Education and awareness-raising about the benefits of renewable energy are key

to securing the support of the local population and promoting a fair and inclusive energy transition.

The future prospects for wind energy in Brazil are promising, with the potential for expansion into new areas and the implementation of innovative technologies that increase generation efficiency. The development of energy storage systems and integration with other renewable sources, such as solar, can provide a more stable and reliable energy supply. As the world moves towards a more sustainable energy model, Brazil has the opportunity to lead this transition, taking advantage of its wind potential and contributing to a more sustainable future, both nationally and globally. Continued investment, technological innovation and a commitment to sustainability are essential if the country is to achieve its climate goals and promote the well-being of future generations.

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