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Socio-environmental Impacts of the Installation and Operation of Wind Farms in Brazil

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ABSTRACT
The expansion of wind energy in Brazil has significantly contributed to the energy transition and the reduction of greenhouse gas emissions. However, the installation and operation of wind farms entail considerable socioenvironmental impacts. This study aimed to analyze the socioenvironmental impacts arising from the installation and operation of wind farms in Brazil, seeking to understand the environmental and social consequences generated by this renewable energy source. The methodology adopted was an integrative literature review, enabling a comprehensive analysis of studies published between 2019 and 2024. Significant environmental impacts were identified, such as vegetation degradation, soil compaction, wildlife displacement, and landscape alterations, as well as social challenges faced by local communities, including land access restrictions, property damage, and frustrations with unfulfilled economic promises. The research concluded that the development of more inclusive public policies and effective mitigation strategies is essential to ensure a balance between energy growth and socioenvironmental preservation. The involvement of affected communities and transparency in implementation processes are deemed essential for a sustainable expansion of wind energy in Brazil.

Keywords*: Wind energy; Socioenvironmental impacts; Energy matrix; Sustainability; Public policies. country.*

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I. INTRODUCTION

The expansion of wind energy, driven by the growing demand for renewable sources and the need to diversify the energy matrix, stands as one of the primary strategies to sustainably meet energy demands and reduce dependence on fossil fuels. However, although the growth of wind farms represents progress toward a green economy, it also brings socio-environmental challenges that deserve attention. The installation and operation of these structures directly impact the environment and local communities, making it essential to critically analyze the effects of this energy model (Azevedo; Nascimento; Schram, 2017; Medeiros Júnior; Miranda, 2018).

In Brazil, which holds one of the world's greatest wind potentials, particularly in the Northeast and South regions, wind energy has become one of the main resources for generation, contributing significantly to the country's renewable energy total. Nonetheless, the accelerated expansion of this sector raises critical issues regarding associated socio-environmental impacts, such as biodiversity loss and the transformation of traditional territories (Loiola, 2024).

Environmental impacts include changes in biodiversity, with the displacement of native species and alterations to local ecosystems, along with modifications to soil and landscape that may disrupt the balance of natural resources. Simultaneously, from a social perspective, the establishment of wind farms affects local communities, influencing the economy, land use, and cultural practices, directly impacting the quality of life of traditional populations. In areas occupied by Indigenous, quilombola, or rural communities, these projects may bring both economic opportunities and conflicts of interest and, in some cases, lead to forced displacement (Araújo, 2017; Pinto et al., 2014).

Thus, understanding the range of these impacts becomes essential for developing public policies and environmental management practices capable of mitigating adverse effects and enhancing local benefits. The analysis of socio-environmental impacts, therefore, serves as a fundamental tool to promote energy planning that is responsible, sustainable, and socially just. By shedding light on these challenges, this study aims to contribute to the debate and the formulation of guidelines that ensure the advancement of wind energy in Brazil occurs in an

ethical and sustainable manner, respecting both the environment and the affected populations. This study followed an integrative literature review approach, enabling a comprehensive analysis of the socio-environmental impacts related to the installation and operation of wind farms in Brazil. In this context, the general objective of this study is to analyze the socio-environmental impacts associated with the installation and operation of wind farms in Brazil, considering the effects on the environment and local communities. The specific objectives are as follows: (i) to identify the main environmental impacts, focusing on changes in fauna, flora, and natural resources; (ii) to assess the socioeconomic and cultural effects on local communities; and (iii) to analyze the existing policies and regulations for mitigating these impacts and discuss their effectiveness in the Brazilian context.

This article is structured into five sections, including the introduction. The second section presents the theoretical framework, discussing key concepts and studies on the socio-environmental impacts of wind farms. The third section describes the methodology used in analyzing the effects of wind farm installations and operations. The fourth section provides an analysis of the results, accompanied by a detailed discussion of the findings related to environmental and social impacts. Finally, the last section presents the conclusions, highlighting recommendations for future research and policies that promote sustainability in the Brazilian wind energy sector.

II. MATERIAL AND METHODS

This study followed an integrative literature review approach, allowing for a comprehensive analysis of the socio-environmental impacts related to the installation and operation of wind farms in Brazil. The integrative review is a methodology that enables the inclusion of studies with different approaches, promoting a holistic understanding of the phenomenon under investigation (Souza; Silva; Carvalho, 2010).

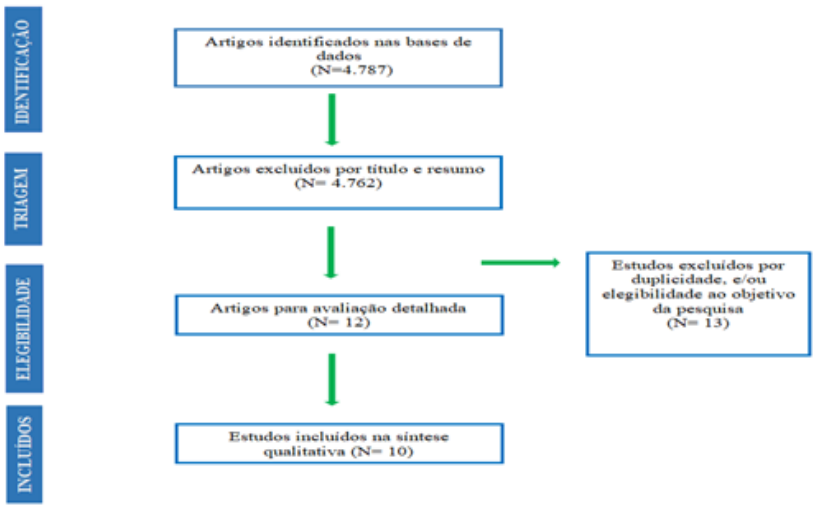
The review was conducted in four main stages: (1) defining the guiding question, (2) establishing inclusion and exclusion criteria, (3) searching for and selecting studies, and (4) critical analysis and synthesis of findings. The guiding question that directed the research was: What are the main socio-environmental impacts associated with wind farms in Brazil? This question was formulated to guide the search and ensure that the selected studies addressed the topic in a relevant and detailed manner.

Studies published between 2019 and 2024, in Portuguese or English, that discuss the environmental and social impacts of wind farms in Brazil were included. Exclusion criteria eliminated studies that did not answer the guiding question or were unavailable in full text. The search was conducted in the SCIELO, PubMed, and Google Scholar databases, using specific keywords such as "environmental impacts," "wind energy," and "social impacts," combined with Boolean operators to ensure a more comprehensive and precise search.

Initially, the titles and abstracts of the articles found were read for a preliminary screening. Then, the full texts of the selected studies were critically analyzed, highlighting key findings on socio-environmental impacts. Relevant data were organized into thematic categories to facilitate interpretation and comparison. Finally, the analysis of the articles was conducted systematically, ensuring a thorough interpretation and contributing to a well-founded discussion on the challenges and opportunities in the wind energy sector in Brazil.

A total of 4,787 studies were found in the previously mentioned databases, of which 4,762 were excluded based on title and abstract, and 13 due to duplication and/or relevance to the research objective, leaving 12 studies for full analysis. Of these, 10 were included in the qualitative synthesis. To better illustrate the data analysis stages, a Flowchart model was chosen to aid in the statistical distribution of the data found, as shown in Figure 1.

Figure 1 – Flowchart showing the study selection according to the databases.



Source: Researchers' Data

After selection, a table was created for the analysis and interpretation of the study data, presenting the author, year, title of the work, general objective, and results, respectively.

III. THEORETICAL FRAMEWORK

This theoretical foundation is organized into three main subtopics, each addressing a critical aspect related to the socio-environmental impacts of wind farms in Brazil: (1) Context of Wind Energy in Brazil. In this first subtopic, the historical development and evolution of wind energy in the country are discussed, emphasizing its potential in the Northeast region and its importance to Brazil's energy matrix. (2) Environmental and Social Impacts of Wind Energy.

The second subtopic examines the primary effects of wind farm installation and operation, covering changes in biodiversity, soil, and landscape, as well as economic and cultural transformations experienced by local communities, with a focus on cases involving traditional populations. (3) Public Policies, Sustainability, and Planning.

The third subtopic explores the environmental laws and policies regulating the wind sector in Brazil, assesses the effectiveness of impact mitigation measures, and underscores the importance of sustainable practices and responsible planning to ensure a balance between energy development and socio-environmental preservation.

3.1 Context of Wind Energy in Brazil

Wind energy has established itself as one of the main renewable sources in Brazil's energy matrix, standing out for its significant growth in recent decades. Brazil possesses one of the largest wind energy potentials globally, especially in the Northeast region, which benefits from consistent, high-intensity winds, ideal conditions for wind energy generation (Salino, 2011).

Historically, wind energy began to be explored in Brazil in the 1990s, with the installation of the first turbine in the Fernando de Noronha Archipelago in 1992, marking the start of a sector that would gain global significance. Later, other areas, such as Minas Gerais, also initiated experimental projects (Silva & Vieira, 2016). The Northeast region stands out by concentrating approximately 90% of the country's wind energy production due to favorable climatic and geographic characteristics. States like Ceará, Rio Grande do Norte, and Bahia lead in installed capacity, significantly contributing to the nation's energy supply. Additionally, wind energy is now the second-largest source in Brazil's electricity matrix, accounting for 10.8% of the total, surpassed only by hydropower, which comprises around 54% (Lisboa, 2022).

In 2023, Brazil reached a milestone of 1,027 installed wind farms, totaling 30.45 GW of capacity—a growth of 18.79% compared to December 2022, when the capacity stood at 25.63 GW. Currently, wind energy represents about 15% of Brazil's electricity matrix, with 30,000 MW of power, contributing to a total national capacity of 200,000 MW. The 1,003 wind farms across 12 states supply energy to 41 million households. In 2023 alone, 123 new parks were installed, adding 4.8 GW of capacity, positioning Brazil as the third-largest country globally in new wind installations, behind only China and the United States, according to the Global Wind Energy Council (GWEC). Globally, the year also set a record with 116.6 GW of new capacity installed, according to ABEEólica data (Muta, 2024).

The growth of wind energy in Brazil has been driven by public policies that promote renewable sources, such as specific energy auctions and attractive financing lines. These initiatives aim to diversify the energy matrix, reduce dependency on fossil fuels, and foster sustainable development (Agra Neto, 2015). Although the accelerated growth of wind energy represents a significant step forward in Brazil's energy transition, it also presents complex challenges related to environmental and social impacts, requiring critical analysis that will be explored in the following sections of this work.

3.2 Socio-environmental Impacts of Wind Energy

Wind energy, while a renewable and clean source with significant potential to mitigate greenhouse gas (GHG) emissions, is not without substantial environmental and social impacts, which must be carefully considered and managed. From an environmental perspective, wind farms cause considerable landscape modifications and can interfere with local fauna.

Azevedo, Nascimento, and Schram (2017) highlight that the main impacts include noise generated by turbines, which, despite technological advancements, may still affect the well-being of nearby communities. Additionally, the presence of these structures alters the landscape, leading to mixed perceptions, from symbols of progress to visual displeasure, especially in scenic or tourist areas.

Costa et al. (2019) note that the construction of wind farms in the state of Ceará has led to the degradation of native vegetation and soil compaction, resulting in water runoff issues and cracks in nearby homes. Communities have also reported that excessive turbine noise disrupts residents' sleep at night. Local avian fauna face significant risks, such as collisions with wind turbines, impacting local biodiversity.

Another critical impact on fauna is the mortality of birds and bats, especially in areas situated along key migratory routes. Pinto, Martins, and Pereira (2017) explain that mitigation measures, such as adjusting turbine locations and implementing visual and auditory deterrents, are necessary to reduce these adverse effects. From a social perspective, wind energy can bring benefits such as job creation and regional economic development. However, it can also lead to conflicts over land use and the displacement of communities. In some cases, the necessary infrastructure affects territories inhabited by Indigenous populations or preservation areas, demanding inclusive and participatory planning to balance economic benefits and social costs (Pinto, Martins, & Pereira, 2017).

In Brazil's semi-arid region, Traldi (2018) argues that these projects can lead to accumulation by dispossession, whereby local communities lose land to capital interests, generating social inequalities and altering territorial occupation. Economic benefits, such as job creation, are primarily concentrated in the construction phase, while opportunities decrease during the operation phase. Additionally, restrictions on territorial access and control over areas near wind farms hinder local populations' mobility, limiting their use of traditional routes. On the other hand, Costa et al. (2019) observe that infrastructure improvements, such as road construction, can benefit some communities but also bring disadvantages, such as increased dust production and accident risk.

3.3 Public Policies, Sustainability, and Planning

The growth of wind energy in Brazil would not have reached current levels without the implementation of strategic and effective public policies that have promoted both sector development and a commitment to environmental sustainability. A significant milestone in this process was the creation of the PROINFA program in 2002. This initiative emerged as a response to the 2001 energy crisis, aiming to diversify the national energy matrix by integrating renewable sources, such as wind energy, into Brazil's electrical system.

According to Cardoso (2020), PROINFA set ambitious goals and provided financial incentives, facilitating access to credit for wind projects and securing long-term contracts with Eletrobrás, which offered investors greater security. In addition to PROINFA, other initiatives, such as energy auctions and Clean Development Mechanism (CDM) projects, have been fundamental to consolidating the wind sector in Brazil.

Silva Júnior et al. (2011) emphasize that CDM projects significantly contributed to the transfer of cleaner technologies, helping Brazil meet its greenhouse gas emissions reduction targets in line with international climate agreements. These projects play an essential role in promoting sustainable development, adhering to the triple bottom line approach, which encompasses economic, social, and environmental benefits.

However, Silva Júnior et al. (2011) also highlight that the effectiveness of these projects depends on continuous integration with national policies that encourage technological innovation and community engagement. Another relevant aspect is the structuring of the wind energy sectoral system in Brazil, which involves a broad network of public institutions, research associations, universities, and private companies.

Nascimento, Mendonça, and Cunha (2012) explain that this network is vital for fostering an environment conducive to innovation, allowing the wind sector to become increasingly competitive on the international stage. Nevertheless, they also stress that while the economic dimension of wind energy is well developed, the social and environmental dimensions still face challenges and are often relegated to secondary importance. This underscores the need for policies that prioritize a balanced approach, where sustainability is not merely a theoretical concept but a practice implemented at every stage of project planning and operation. From a sustainability standpoint, Brazil holds significant potential to become a global leader in renewable energy. However, this requires strategic planning that considers socio-environmental impacts in an integrated manner. The planning of new wind farms should include rigorous environmental impact assessments, taking into account the preservation of flora and fauna as well as minimizing noise and landscape changes, which may affect both biodiversity and local communities. Furthermore, social inclusion should be a priority, ensuring that the involved communities have an active voice in decision-making processes and can economically benefit from the installation of wind farms.

An example of success in this regard is the Serra Branca Wind Complex, located in Rio Grande do Norte. As one of the largest wind complexes in the world, it spans a vast area and includes several interconnected wind farms. The project stands out for its sustainable practices and for having generated thousands of direct and indirect jobs in the region. However, for every success story, challenges remain, such as dependence on government incentives and the complexities of environmental licensing, which can hinder sector expansion. Compared with international experiences, countries such as Denmark and Germany have long-term policies that ensure regulatory stability and encourage public-private partnerships, serving as models for Brazil to improve governance in the wind sector (Hackett, 2021; Taylor, 2023).

In summary, public policies have been instrumental in advancing wind energy in Brazil, but continuous efforts are needed to refine strategic planning and ensure that sector expansion occurs sustainably and inclusively. The future of the wind sector in Brazil will depend on balancing innovation, sustainability, and social benefits, with policies that promote not only economic growth but also environmental preservation and the well-being of local communities.

IV ANALYSIS OF RESULTS

A total of 10 studies were analyzed and included in the research, all of which provided full-text content freely available, with a preference for studies from the last five years (2019–2024) that met the inclusion criteria outlined in Table 1.

Table 1: Selected Studies for Analysis.

Author(s) Year	Title	General Objective	Results
Ferreira; Camacho; Guimarães (2019)	Perception of Socio-environmental Impacts of Wind Farm Implementation in the Community of Ponta do Mel, Areia Branca/RN	To identify local residents' environmental perception of the impacts.	Most of the population supports the wind farms but acknowledges issues such as restricted access to previously available areas and significant visual changes to the landscape.
Costa *et al.* (2019)	Socioeconomic, Environmental, and Technological Impacts of Wind Farm Installation in Ceará	To present the socioeconomic and environmental impacts on Ceará's coast..	The study highlighted native vegetation degradation, water runoff issues due to soil compaction, and economic benefits mainly concentrated in the initial phase
Leite; Picchi (2019)	Socio-environmental Impacts from the Implementation and Operation of Wind Farms in the State of Paraíba	To analyze the specific impacts of wind energy and the mitigation policies.	The study found that mitigation policies are insufficient, leading to the destabilization of local communities and raising questions about the sustainability narrative of the projects.
Leuzinger; Coutinho (2019)	The Implementation of Wind Farms and Socio-environmental Impacts on Indigenous and Traditional Populations	To examine the impacts on indigenous and traditional populations.	The study indicated that, despite legal protections for indigenous peoples, traditional communities remain vulnerable to displacement and negative territorial impacts.
Oliveira (2020)	"They Only Use the Wind": Socio-environmental Impacts of Wind Farm Installation on the Coast of Maranhão	To study the impacts in Maranhão and the narratives used to legitimize the projects.	The study identified conflicts between local communities and companies, destruction of ecosystems such as dunes and lagoons, and dissatisfaction with the promised economic benefits.
Silva *et al.* (2022)	Socio-environmental Impacts of Wind Farms in Brazil: A Literature Review	To investigate the environmental and social impacts of wind farms in Brazil.	The study gathered evidence that the impacts cover environmental, social, economic, and cultural spheres, and emphasized the need for more effective mitigation policies.
Menezes; Guimarães (2022)	Socio-environmental Impacts of Alternative Energy Sources on Communities Surrounding Wind Farms	To evaluate the impacts on communities near wind farms in Rio Grande do Norte and Bahia.	The study observed that the wind farms significantly altered the landscape and quality of life, although they contributed to energy diversification and regional development.
Cruz (2023)	Analysis of Socio-environmental Impacts Caused by the Installation of a Wind Farm in Queimada Nova Municipality, PI	To analyze the socio-environmental impacts of wind farms in Queimada Nova.	The study identified that the wind farms generated constant noise and modifications to the landscape, affecting residents' well-being and causing the displacement of local fauna.
Mota (2023)	The Socio-environmental Impacts of the Construction of the Icapuí Wind Farm, CE	To analyze the socio-environmental effects of wind farm construction in Icapuí.	The study highlighted issues such as cracks in residences, blocking of local roads, and environmental losses, all of which affected the way of life of the community.
Barros *et al.* (2024)	Social and Environmental Impacts of Wind Farm Implementation: A Critical Analysis	To investigate the social and environmental impacts associated with the expansion of wind energy.	The study emphasized deficiencies in planning, with severe impacts on biodiversity and the territorial organization of communities, requiring effective mitigation strategies.

Source: Researchers' Data

The environmental impacts associated with wind farms are diverse and significant, affecting both the fauna and flora of the regions where projects are implemented. According to Ferreira, Camacho, and Guimarães (2019), the installation of wind farms in areas such as Ponta do Mel, Areia Branca/RN, results in significant changes in the landscape and restrictions on access to areas that were previously used by communities. Costa (2019) complements this by highlighting the degradation of native vegetation and water drainage issues caused by soil compaction, which have implications for environmental conservation.

Furthermore, Oliveira (2020) points out that the destruction of ecosystems, such as dunes and lagoons, along the Maranhão coastline, compromises environmental balance, leading to conflicts over natural resource use. Another critical issue is the impact on fauna. Cruz (2023) observes that the wind turbines, in addition to altering the landscape, generate noise that affects the behavior of local animals, leading to the displacement of species.

Leuzinger and Coutinho (2019) draw attention to the fact that even in legally protected areas, such as indigenous territories, biodiversity continues to face threats due to the proximity of wind farms. These effects are exacerbated by the lack of effective strategies to mitigate bird and bat collisions with turbines. Socially, wind farms also present considerable challenges for local communities. The perception of impact varies, but there is a consensus on the negative changes in quality of life.

Mota (2023) discusses how the construction of wind farms in Icapuí-CE caused cracks in residences and blocked roads used by the population, complicating local mobility. Silva et al. (2022) report that traditional communities, such as those in northeastern Brazil, face land appropriation and deforestation, which alter cultural practices and ways of life. Community dissatisfaction with unmet promises is also a key point.

Menezes and Guimarães (2022) emphasize that while wind farms bring temporary economic benefits, such as jobs during construction, these benefits are not sustained in the long term. The expectations raised around long-term improvements often do not materialize, creating frustration and distrust among local residents.

Barros et al. (2024) add that the territorial organization of communities is often disrupted, creating social and economic tensions that could have been avoided with more inclusive planning. The interconnection between social and environmental impacts is evident. Environmental degradation directly affects the daily lives of people who depend on these ecosystems for subsistence and cultural activities.

Leite and Picchi (2019) highlight that current mitigation policies are insufficient and often exacerbate social problems rather than resolve them. This insufficiency reflects the lack of planning that considers the specificities of local communities and their needs. The combined analysis of these studies reinforces the urgent need for a balance between energy development and the preservation of ecosystems and local communities.

Negative impacts cannot be overlooked in the pursuit of renewable energy progress, and more effective mitigation strategies must be adopted to ensure that wind farm development occurs in a sustainable and fair manner. It is essential that public policies be improved to address these challenges holistically, ensuring environmental protection and improving the quality of life for impacted communities.

IV. DISCUSSION AND CONCLUSION

This study aimed to analyze the socio-environmental impacts of the installation and operation of wind farms in Brazil, based on an integrative review of ten relevant studies. Wind energy, as a renewable source and a key component of sustainable energy transition, presents a paradox: despite its undeniable environmental benefits, it also generates negative consequences for the environment and local communities. Environmental impacts include the degradation of native vegetation, soil compaction, water drainage issues, constant noise, and displacement of wildlife.

The modification of landscapes and threats to biodiversity are critical issues that need to be addressed with more effective mitigation strategies. Socially, communities near wind farms face challenges such as displacement, restricted access to land, property damage, and frustration with unmet promises of long-term economic development.

The lack of adequate planning and inclusive public policies intensifies conflicts and the vulnerability of these populations. In light of this, it is concluded that a balance between energy development and socio-environmental preservation is necessary. The advancement of wind energy should be accompanied by robust public policies that ensure the protection of ecosystems and the inclusion of affected communities in the decision-making process.

Transparency, continuous dialogue, and environmental responsibility are crucial to making wind energy expansion in Brazil truly sustainable. Future studies should explore practical solutions to minimize these impacts, such as improving technologies that reduce wildlife collisions and implementing governance models that ensure social equity. Thus, it is hoped that this work contributes to the debate on best practices for wind energy planning

and management, promoting development that respects both the environment and the human populations that depend on it.

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