Northeastern Brazil in the shadow of wind turbines: challenges and socioenvironmental impacts of the energy transition

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Abstract

Although wind energy is recognized as a "clean" energy source, research indicates challenges and negative socio-environmental impacts resulting from the installation of wind farms that affect local communities in the Agreste region in Pernambuco. This study was developed in order to analyzed the socio-environmental challenges and impacts of wind turbines in northeastern Brazil and a sustainable development index, highlighting the opportunities and dilemmas this region faces in the shadow of these installations. Data were collected through individual interviews with residents of rural communities surrounding wind farms within a radius of up to 500 meters from wind turbines. Five dimensions were evaluated: environmental, technical-productive, economic-productive, sociocultural, and political-institutional. Subsequently, an integrated sustainable development index (ISD) was calculated that considered 30 indicators. The integrated diagnosis highlights vulnerabilities and obstacles associated with living alongside wind turbines in the Agreste region. Additionally, this work emphasizes the negative impact that these wind turbines have on the quality of life and daily routine of local farmers. An average ISD of 0.413 was observed and classified as critical in all studied municipalities except Venturosa, which showed a trend toward stability. In summary, despite the purpose of renewable energies to promote sustainability, the identified situation points to low local environmental preservation.

Keywords: Renewable energies. Agreste region. Family agriculture. Sustainability.

Introduction

Rapid population growth and urban expansion have triggered a series of contemporary challenges, notably a significant increase in energy demand and the rising emissions of greenhouse gases. In recent years, the need for electrical energy has indisputably surged, which has been driven by technological development and an incessant quest for a better quality of life (CARSTENS, CUNHA, 2019).

However, this escalating demand for electrical energy comes hand in hand with significant environmental challenges. Increasingly stringent restrictions regarding the use of fossil fuel-based resources and limitations in harnessing hydroelectric potential are primarily driven by the pressing need to mitigate the impacts of climate change and reduce adverse socio-environmental effects associated with the construction of large reservoir-based hydroelectric power plants (BOTELHO *et al.*, 2022; DRANKA, FERREIRA, 2020).

The urgent need to gradually replace fossil fuels with more sustainable energy sources has gained prominence in response to escalating global concerns about climate change. In this scenario, renewable energy sources emerge as a high-priority solution to achieve a socioeconomically and ecologically viable sustainable economy (DRANKA, FERREIRA, 2020).

Under a global agreement, Brazil has committed to reducing its greenhouse gas emissions (GHG) by 43 % below 2005 levels by the year 2030. To attain this ambitious target, the country has set specific objectives, including a substantial increase in the proportion of renewable energy sources in its total energy matrix by the same year (LUCENA, LUCENA, 2019; LEITE *et al.*, 2020). Currently, the energy sector is predominantly dominated by hydroelectric power (58.6 %), followed by wind energy (16.3 %) (EPE, 2021).

Wind energy is widely recognized as a clean energy source, since it does not emit pollutants into the environment, and only causes negative impacts in the areas where wind farms are located (LUCENA, LUCENA, 2019). In Brazil, the Northeast Region stands out as an epicenter in wind energy generation and has attracted significant interest from sector investors. This prominence is due to the constant and stable presence of the South Atlantic trade winds that provide highly favorable conditions for electricity production in the region (DANTAS *et al.*, 2019; SILVA, GALVÃO, 2022).

The state of Pernambuco plays a prominent role in the wind industry and supplies over 60 % of the Northeast Region with its energy. This leadership position stems from the exceptional quality of the winds in the region that are characterized by their high intensity and low turbulence (SILVA, GALVÃO, 2022). Additionally, the location of the Port of Suape offers ideal logistical advantages for the installation of wind farms, which has further consolidated the importance of this state in generating sustainable energy (DANTAS *et al.*, 2019).

However, it is important to highlight that, prior to the installation of wind farms, project assessments are often limited to superficial analyses focused mainly on technical and economic viability. In many cases, only a Simplified Environmental Report (Relatório Ambiental Simplificado – RAS) is required, which does not adequately account for the social and environmental complexities involved (MORAIS, BAIARDI, 2025). As a result, the perceptions and lived experiences of local populations are frequently overlooked in official planning processes. Despite this, during the implementation process of wind farms in northeastern Brazil, there is a public narrative promoting the idea that wind complexes will result in local development in social, economic, and environmental terms (PINTO *et al.*, 2017; GORAYEB, BRANNSTROM, 2020), and environmental terms, often without critically addressing the real impacts on affected communities.

Despite the evident advantages associated with the adoption of wind energy, there are also disadvantages that lead to significant negative impacts. For example, the visual impact, noise emissions, modifications to the local microclimate, loss of soil moisture and nutrients, deforestation, and other changes to the vegetation. Some changes are necessary to allow trucks and tractors to go between the towers and for site preparation before construction (CAMPÊLO *et al.*, 2020; HOFSTAETTER, AZEVEDO, 2021; SOBRINHO JUNIOR *et al.*, 2022).

Therefore, the pursuit of economic development and reducing GHG should not overlook the direct impacts on local communities. It should be accompanied by careful and participatory planning that considers not only the macroeconomic benefits but also the preservation of the well-being and quality of life of the people living near these installations. Sustainable development demands an integrated approach that balances renewable energy goals with respect for local communities and environmental protection.

In this context, it is crucial to conduct assessments that consider the socioeconomic and environmental dimensions of wind farm installations, which encompass impacts on local

communities, economic implications related to government policies and infrastructure, as well as environmental consequences (DANTAS *et al.*, 2019). The main challenge is to balance the benefits of wind energy with environmental preservation and the well-being of local communities.

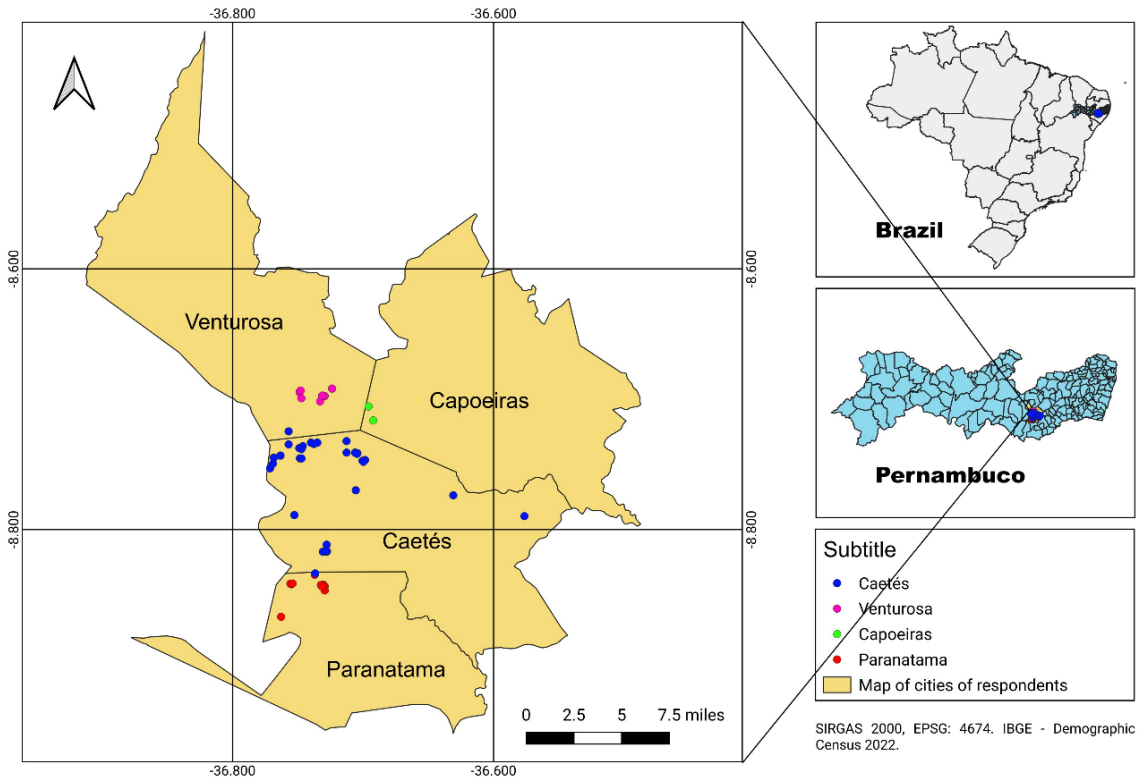
Energy transition has emerged as a globally important topic in recent decades, since the world faces the pressing need to reduce dependence on fossil fuels and mitigate climate change. However, implementing this energy transition has challenges, both from socio-environmental and economic perspectives. Thus, this study was developed in order to analyze the socio-environmental challenges and impacts of wind turbines in northeastern Brazil and a sustainable development index, with the goal of highlighting the opportunities and dilemmas that this region faces in the shadow of these installations.

Material and methods

The study was carried out between May and July 2023 in the Agreste region in Pernambuco within four municipalities, Paranatama, Venturosa, Caetés, and Capoeiras, in the Northeast Region of Brazil (Figure 1). The Agreste region in Pernambuco is geographically situated between the Zona da Mata and the Sertão of Pernambuco, according to data from the Territorial Information System (TIS) of the Ministry of Agrarian Development (MDA).

This region extends across the Borborema Plateau, with altitudes ranging from 400 to 800 meters, and reaches up to 1.000 meters in the Garanhuns microregion. It covers an area of approximately 13.153.50 km^2 and encompasses 20 municipalities, including the four municipalities studied. The climate in this area is classified as humid tropical with a dry summer. The rainy season begins during

Figure 1. Location map of the study municipalities, showing the distribution of data collection points in the Agreste region in Pernambuco.



Source: authors (2023)

autumn and spans the winter and early spring. The annual average temperature and relative humidity are 21.1°C and 82.5 %, respectively, and the average annual precipitation is 781 mm (ALMEIDA *et al.*, 2015).

Data collection involved 73 individual structured interviews with residents of rural communities located within a 500-meter radius of wind turbines, using a quali-quantitative, exploratory approach. An initial mapping identified 561 households, and a statistical sample size calculation (95 % confidence level, 5 % margin of error) indicated a minimum of 228 interviews. Of the 228 households visited, 145 were either unoccupied or the residents refused to be interviewed, reducing the effective sample to 73 interviews which were successfully completed due to additional logistical challenges.

To enhance the robustness of the quantitative analysis, each indicator was measured using data triangulation techniques combining structured interviews, direct field observations, and documentary records to ensure data reliability. Although the sample size was constrained by logistical and social factors, the 73 interviews provided sufficient representation to capture the recurring socio-environmental patterns across the studied municipalities. Each municipality was treated as an analytical unit, with multiple households sampled per location to account for community's variability. Data collection spanned over two months, allowing temporal consistency and minimizing potential seasonal bias. Statistical analyses included the calculation of mean indices per dimension and overall integrated sustainable development index (ISD) scores, facilitating comparative assessments and interpretation of sustainability levels across locations. This design ensures that the study might be replicated in similar rural contexts, providing a transparent framework for applying the ISD methodology under field constraints.

Five dimensions were analyzed (environmental, technical-productive, economic-productive, sociocultural, political-institutional) following an assessment method proposed by Sepúlveda (2008) to create an integrated sustainable development index. Each dimension analyzed consisted of six indicators, each varying from one to three questions, totaling 43 questions, along with 11 additional questions characterizing the profile of the interviewees. In total, approximately 73 family units were visited and interviewed over two months, between May and July 2023.

The research strictly adhered to the guidelines established in Resolution 466 of 2012 by the National Health Council (CNS) and followed all relevant regulations to ensure ethical and legal integrity. Furthermore, the Ethics Committee for Research with Human Subjects in Pernambuco evaluated and issued a favorable opinion with protocol number 5.533.666.

Finally, an index for each dimension was calculated to better analyze each family unit using formulas proposed by Sepúlveda (2008), where a higher index indicates a higher degree of sustainability in that location. The relationship was evaluated in terms of its impact, whether positive or negative, on the community and/or the environment concerning sustainable development. This means the following: a) if the relationship is positive, the higher the indicator, the better the index, and the lower the indicator, the worse the index; and b) when a negative relationship was identified, a higher indicator would mean a worse index and a lower indicator would mean a better index. Thus, the data varied on a scale where the minimum value was 0 (zero) and the maximum was 1 (one), with an increasing range of levels symbolizing the state of sustainability: collapse, critical, unstable, stable, and optimal (interpreted according to Figure 2).

The formula used for calculating indicators that have a positive relationship with sustainability was the following:

$$f(x) = (x - m) / (M - m)$$

For indicators that exhibit a negative relationship with sustainability, the following formula was used:

$$f(x) = (x - M) / (m - M)$$

Where:
f(x) = represents the numerical value of the index for each variable (indicator);
x = is the value of each variable (indicator) for an analytical unit within a specific time interval;
m = represents the minimum value for each variable (indicator) in a given period; and
M = is the maximum value for each indicator in a given period.

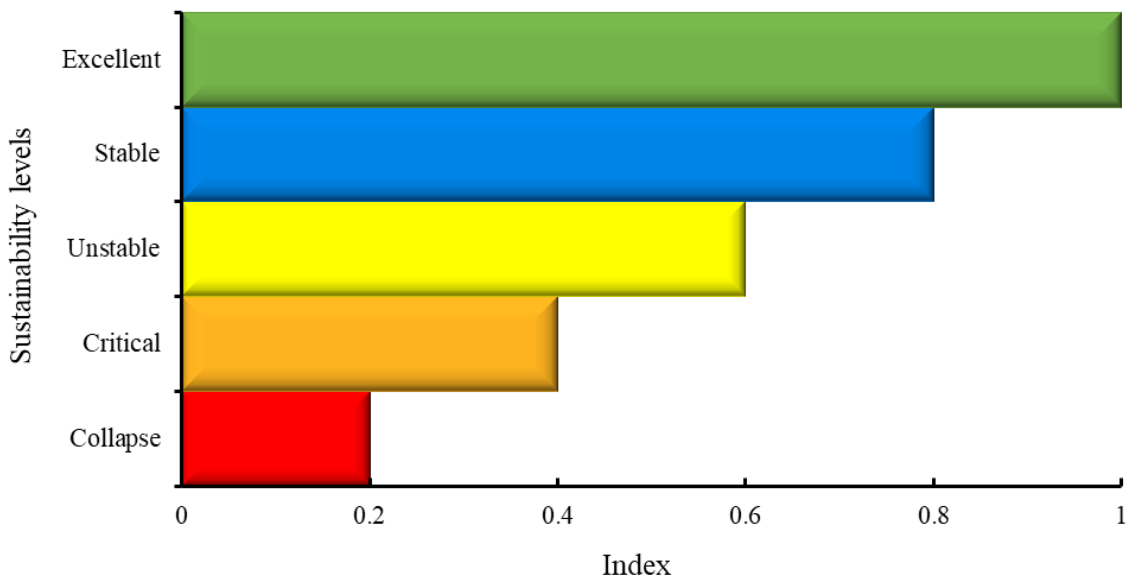
Results and discussion

The questionnaires were administered in rural communities across the four municipalities under study: Caetés, Capoeiras, Paranatama, and Venturosa. A total of 21 communities were visited, and significant data was found. Notably, it was found that 53 % of the respondents were over 40 years old, and 66 % of them were female. Agriculture stood out in this study as the main source of livelihood for families in these areas.

It is crucial to note that the majority of the farmers have only completed elementary school, making them more vulnerable to the impacts of these ventures. This not only highlights a deficiency in efficient public policies for the education of young adults in the region but also the fact that approximately half of the respondents in all municipalities have a family member benefiting from social programs, as illustrated in Figure 3. This indicates that these families are considered by the Brazilian government as living in poverty or extreme poverty (GUSMÃO *et al.*, 2012).

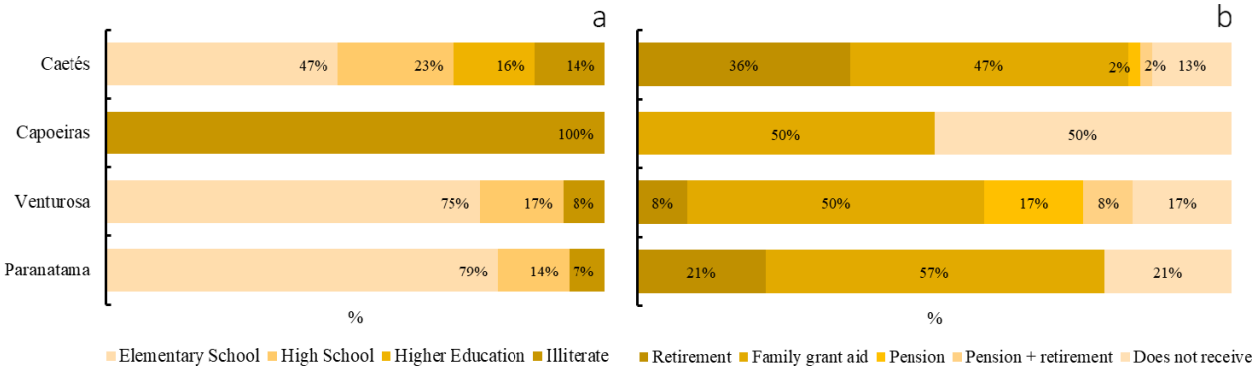
It was noted during the development of this study that the absence of oversight and specific regulations for the installation of wind farms near rural communities has strengthened the negotiating power of companies seeking to implement these activities inappropriately. In this scenario, companies have offered minimal social benefits in exchange for transferring significant environmental costs to the population in these areas.

Figure 2. Sustainability level classification, based on the index and color.



Source: adapted from Sepúlveda (2008).

Figure 3. Profile of interviewees in the municipalities of Caetés, Capoeiras, Venturosa, and Paranatama, Pernambuco, Brazil. (a) Level of education and (b) type of financial assistance they receive.



Source: authors (2023)

As highlighted by Santos (2014), the major companies leading these ventures take advantage of these locations due to lower land costs, inadequate public services, and deficient infrastructure. In exchange for the negative impacts caused by the installation of wind turbines, they provide minor improvements to residential infrastructure and local roads. In these circumstances, communities face significant challenges, including high unemployment rates, limited political influence to represent their interests, and scarce resources to seek alternatives and healthier living conditions away from wind complexes. Thus, it is the communities themselves that end up bearing the burden of these ventures that generate socio-environmental damage, which are often the same ventures that claim to contribute to the so-called sustainable development.

Various authors support the central narrative behind the implementation of these complexes in less advantaged areas of the Northeast Region by justifying it as a way to boost local development (CAMPÊLO *et al.*, 2020; GORAYEB, BRANNSTROM, 2016). However, what has been witnessed in the Northeast Region is traditional communities losing their peace and quality of life due to energy generation, which is often directed to other regions of the country through a national interconnected system (NIS) (GALVÃO *et al.*, 2020).

These communities rarely receive benefits, such as discounts or exemptions on their household energy bills, and the jobs announced as being generated for the region are often temporary (LEITE, PICCHI, 2019). In this context, the disproportion between the impacts caused and the development becomes evident, and this often goes unnoticed or unacknowledged by the local residents.

Despite the urgency and necessity of this energy transition to combat environmental impacts caused by burning fossil fuels, the implementation of wind energy, which is considered a clean alternative, has not occurred in a completely sustainable manner. Studies indicate that while these companies often provide local benefits, such as infrastructure improvements and job creation, they also generate negative impacts, such as vegetation suppression (SOBRINHO JUNIOR *et al.*, 2022), increased susceptibility to soil erosion (DAI *et al.*, 2015), alterations in local income sources, environmental modifications, and risks to biodiversity (NERI *et al.*, 2019). Residents express dissatisfaction with issues previously reported by several authors, including significant noise (BAKKER *et al.*, 2012; CAMPÊLO *et al.*, 2020), the impact on fauna (THAXTER *et al.*, 2017) and flora (GALVÃO *et al.*, 2020), changes in the landscape, quality of life, well-being, and impacts on plant and animal production (NASCIMENTO *et al.*, 2020).

Wind turbines cause changes in the direction and speed of winds, influencing the local climate (KEITH *et al*., 2004), which may be closely related to the low indices in the technical- and economic-productive dimensions (Figure 4). Some residents reported perceived in crop productivity, which they associate with factors such as increased soil evaporation or a decrease in pollinator activity. Although these effects are not yet fully substantiated by local empirical data, they reflect the community's perceptions and highlight the need for further investigation into the environmental impacts of wind energy infrastructure in semiarid agroecosystems.

Additionally, it is important to note the occurrence of bird collisions with wind turbines (THAXTER *et al.*, 2017; GALVÃO *et al.*, 2020) that result in significant mortality rates, which is consistent with other reports found in the literature (CAMPÊLO *et al.*, 2020; TAVARES, 2020). Therefore, it is essential to delve deeper into the analysis of these impacts to find integrated solutions that minimize adverse effects and ensure a balanced coexistence between the wind turbines and environmental preservation.

The integrated diagnosis conducted with residents surrounding wind turbines in the four municipalities highlights the vulnerabilities and obstacles associated with cohabitation alongside wind turbines in the Agreste region in Pernambuco. Furthermore, it underscores the negative impact of these wind turbines on the quality of life and daily routine of local farmers. This study employed the integrated sustainable development index proposed by Sepúlveda (2008). The results revealed indices across the five studied dimensions that, based on the classification (Figure 2), indicate sustainability scenarios ranging from critical to unstable in all studied municipalities (Figure 5).

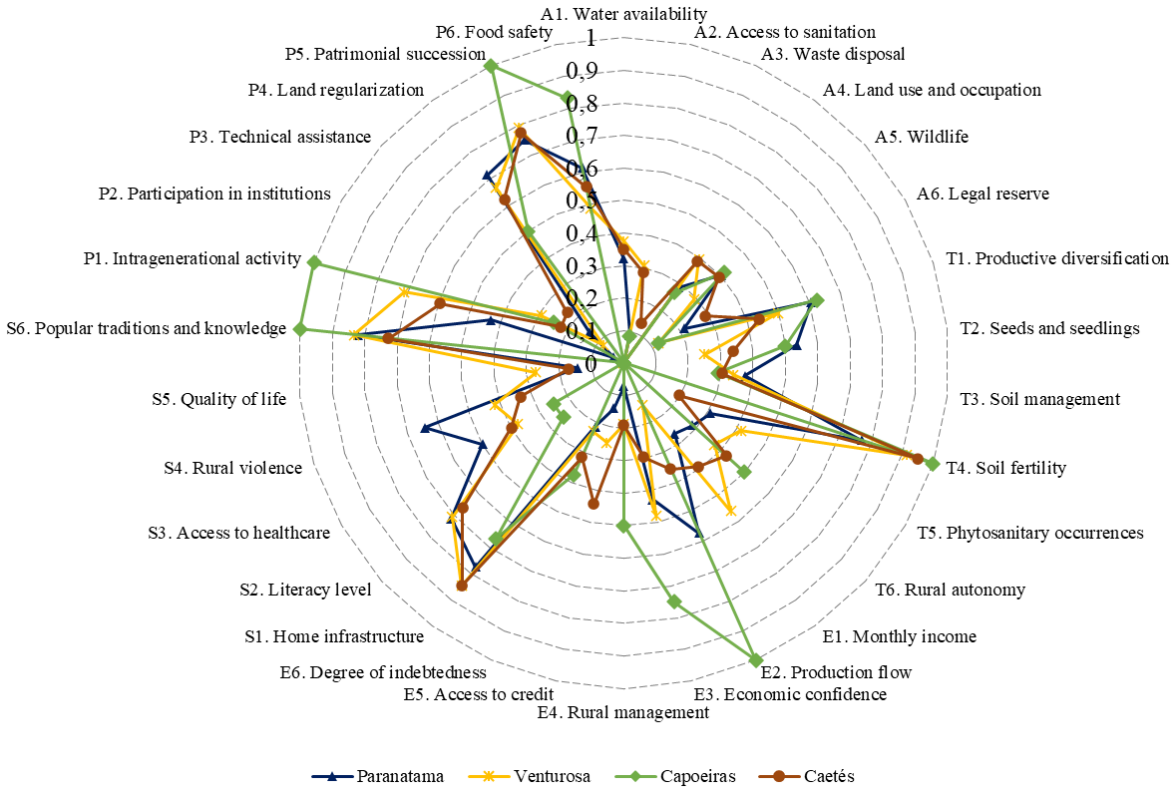
These findings contradict the proposed sustainable development for the country's energy sector, which aligns with the 17 Sustainable Development Goals (SDGs) of Agenda 2030. This contrast emphasizes the need for prior, effective, and sustainable assessments in regions where wind farms are implemented and managed that consider both national goals and the well-being of local communities.

Overall, the analysis of the five dimensions (environmental, technical-productive, economic-productive, sociocultural, and political-institutional) revealed distinct patterns among the studied municipalities. Caetés stood out for having higher indices in the environmental dimension, while Capoeiras excelled in the technical-productive, economic-productive, and political-institutional dimensions. Paranatama, in turn, had the best indices in the sociocultural dimension. However, it is important to note that none of these municipalities had stable or excellent sustainability classifications for the studied aspects, as indicated in Figure 5.

These results clearly point to the impacts arising from the implementation of wind turbines in the vicinity of rural communities. Despite promises of sustainable development, the closest communities do not benefit, not even from discounts on their energy bills. Such indices underscore the urgent need for a more comprehensive analysis and continuous monitoring of these areas. Thus, the importance of companies adopting mitigation measures that promote a balance between sustainable development in the energy sector in the region and the well-being of the affected communities has become evident.

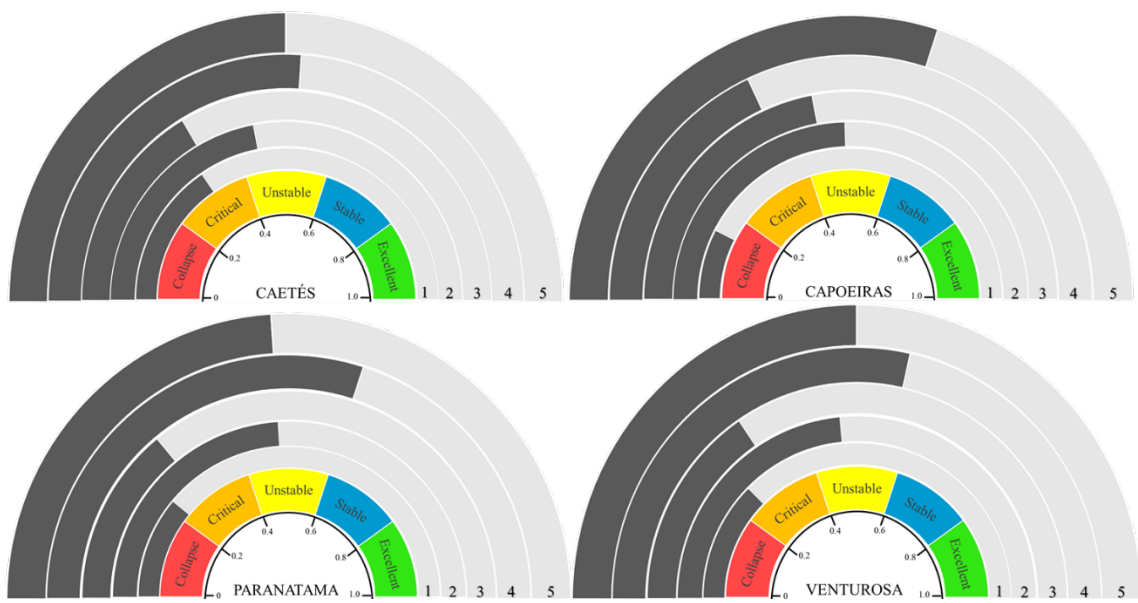
The low indices found for the environmental dimension are notable for all studied municipalities, which exacerbates the situation, especially because the expansion of renewable energies aims primarily to reduce greenhouse gas emissions and should align with the 17 SDGs. However, the analysis reveals a scenario marked by low local environmental preservation. Identified issues include occurrences of wildfires

Figure 4. Biogram of the integrated sustainable development index (ISD) for all dimensions studied in the municipalities of Caetés, Capoeiras, Venturosa and Paranatama, Pernambuco, Brazil.



Source: authors (2023)

Figure 5. Indices of the five dimensions, (1) environmental dimension, (2) technical-productive dimension, (3) economic-productive dimension, (4) sociocultural dimension and (5) political-institutional dimension, and their classification in the four studied municipalities, Caetés, Capoeiras, Paranatama and Venturosa, in the state of Pernambuco, Brazil.



Source: authors (2023)

and deforestation, associated with challenges related to precarious water supply and the absence of basic sanitation in some regions. Additionally, soil erosion processes were observed (Figure 4 and 5).

During data collection, residents reported that the implementation process of wind farms led to deforestation to open access roads for machinery, an observation also reported by other authors (CAMPÊLO *et al.*, 2020; HOFSTAETTER, AZEVEDO, 2021). This process not only modifies the local habitat but also results in the release of CO_2 emissions due to vegetation removal. This counterpoint contradicts the central purpose of renewable energies, which is to mitigate the impacts of climate change.

It is important to emphasize that wind energy has stood out in the global and national electrical scenario in recent years, driven by the force of the winds. Considered a renewable and sustainable source, especially regarding its generation, wind energy is recognized as an environmentally friendly alternative. The state of Pernambuco, along with the entire Northeast Region of Brazil, has enormous potential for growth and development through this energy matrix due to its favorable geographical location (DANTAS *et al.*, 2019; SILVA, GALVÃO, 2022). However, for this policy to be effective, it is crucial to implement it appropriately by respecting the principles of sustainable development and local communities, as well as fostering open dialogue to ensure active and democratic participation.

The analysis of the sociocultural and political-institutional dimensions, fundamental for cultural preservation and local identity, conflict resolution, land access, rural exodus management, promotion of quality of life, as well as for community participation and decision-making, rights assurance and social justice, revealed low indices for all studied municipalities. This finding highlights that wind farms have impacts on all dimensions considered relevant for achieving local sustainability, encompassing environmental, social, and economic pillars.

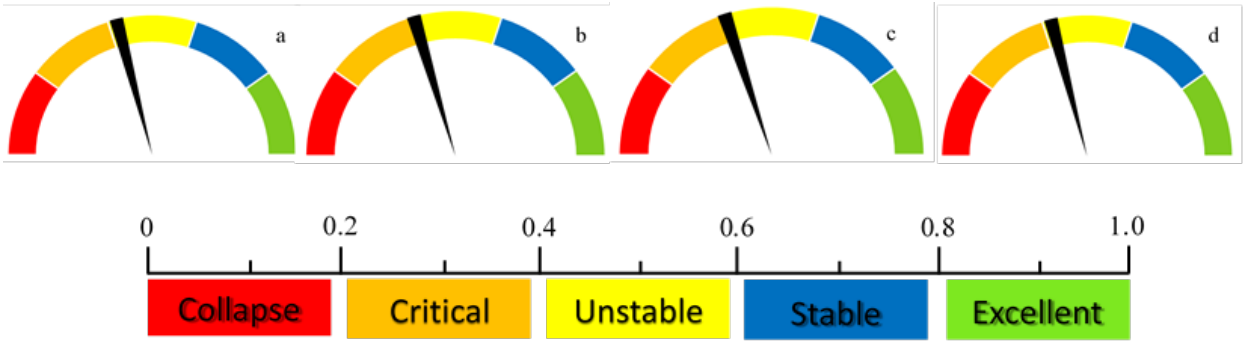
From a sociocultural aspect, negative effects on local traditions and knowledge resulting from changes in the communities' lifestyles were observed (Figure 4). The presence of turbines has also generated conflicts, especially related to land access and an increase in rural exodus in the region. The latter is widely influenced by reduced productivity, mainly due to the constant noise from the turbines, which negatively impacts the residents' quality of life.

For the political-institutional dimension, it becomes essential to analyze the governance involved in the implementation of these projects by considering the participation of communities in the decision-making process to ensure their rights are respected. A solid political and institutional vision plays a crucial role in mitigating the negative impacts caused by the implementation and maintenance of wind farms, which promotes real sustainable development.

The integrated sustainable development index (ISD) had an average of 0.413, which is classified as critical in all studied municipalities, except Venturosa that had a tendency towards stability (Figure 6). Derived from indicators in the environmental, technical-productive, economic-productive, sociocultural, and political-institutional dimensions, this index offers a more comprehensive understanding of sustainability in these communities.

An in-depth analysis of the ISD reveals specific areas that require attention and intervention (Figure 4). The average suggests positive aspects but also challenges to be overcome. Sectors with well-established sustainability can serve as a model for improvements in other areas, highlighting sustainable practices in production, efficient resource management, and effective community participation. Dimensions with lower scores indicate areas where wind farms may

Figure 6. Sustainable development indices and their overall classification for the four studied municipalities, Caetés (a), Capoeiras (b), Paranatama (c) and Venturosa (d), in the state of Pernambuco, Brazil.



Source: authors (2023)

have more negative impacts or where sustainable practices need reinforcement.

These indices have the potential to influence policy decisions and management practices, encouraging the implementation of corrective measures and the strengthening of sustainable practices. In summary, the integrated sustainable development index is a valuable tool for understanding the overall impacts of wind farms in the studied municipalities by enabling a more informed and strategic approach to address specific issues and promote long-term sustainability.

Given this context, and especially in countries like Brazil, where the environmental, social, and economic impacts of wind energy are still not clearly understood across the various regions with favorable potential for this energy resource, it becomes essential to adopt public policies that enforce stricter territorial planning and establish minimum distance regulations between wind turbines and rural communities, ensuring the protection of residents' well-being.

Additionally, it is recommended that companies operating wind farms implement mandatory socio-environmental compensation plans, including continuous environmental monitoring, community benefit-sharing programs, and inclusive decision-making processes. Strengthening local governance mechanisms and promoting transparency in land negotiations are also crucial steps toward minimizing socio-environmental conflicts and fostering truly sustainable wind energy development.

Conclusions

The integrated diagnosis reveals that, although wind farms bring certain benefits, they significantly affect the quality of life of local farmers. The sustainability index exposes a critical scenario for semiarid agroecosystems, marked by low environmental preservation and heightened vulnerability to the energy transition. This calls for urgent, targeted public policies to mitigate negative impacts and ensure that wind energy development aligns with the well-being of communities and environmental integrity.

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