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Zoneamento para exploração da energia eólica no Ceará com uso de sistemas de informação geográfica (SIG) e análise multicritério

Zoning for exploration of wind energy in Ceará with the use of geographic information systems (GIS) and multicriteria analysis

Zonificación para la exploración de la energía eólica en Ceará con el uso de sistemas de información geográfica (SIG) y análisis multicritério

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Daniela Cadore Vale
ORCID: https://orcid.org/0000-0001-8435-8218
Instituto Federal de Educação, Ciência e Tecnologia do Ceará, Brasil
E-mail: danielacadore@yahoo.com.br
Renato Sipelli Silva
ORCID: https://orcid.org/0000-0002-0592-8882
Instituto Federal de Educação, Ciência e Tecnologia do Ceará, Brasil
E-mail: renatosipelli@hotmail.com
Erika da Justa Teixeira Rocha
ORCID: https://orcid.org/0000-0003-2247-3055
Instituto Federal de Educação, Ciência e Tecnologia do Ceará, Brasil
E-mail: erikadajusta@gmail.com
Auzuir Ripardo de Alexandria
ORCID: https://orcid.org/0000-0002-6134-5366
Instituto Federal de Educação, Ciência e Tecnologia do Ceará, Brasil
E-mail: auzuir@gmail.com

Resumo

A energia eólica tem muitas vantagens em comparação com as energias tradicionais, desde a capacidade para reduzir o uso de combustíveis de fósseis bem como a possibilidade de criação de empregos nas áreas em que os projetos são instalados. O crescimento deste tipo de geração no Brasil tem sido impulsionado por um forte interesse dos investidores devido às características dos ventos do país, principalmente do Nordeste. Os ventos são fortes, estáveis e na maior parte do tempo seguem a mesma direção, características que fazem dos parques da região Nordeste terem altos índices de fator de capacidade. Avaliando os dados dos parques eólicos instalados no Ceará, pode-se observar que eles apresentam um dos melhores fatores de capacidade no Brasil e têm valores acima da média mundial. Isto indica e reforça a viabilidade da implantação deste tipo de geração de energia na área. Foi verificado que existem estudos sobre as condições do vento, mas não há estudos que correlacionem esta informação com as condições de infraestrutura do Estado. O objetivo deste trabalho, portanto, é identificar as áreas apropriadas para a alocação e uso da energia eólica no estado do Ceará, através da integração de ferramentas de Sistemas de Informação Geográfica (SIG) e de análise multicritério de tomada de decisão.

Palavras-chave: Parques eólicos; Energias renováveis; Potencial para instalação de parques eólicos; Processo de hierarquia analítica.

Abstract

Wind energy has many advantages compared to traditional energies, from the ability to reduce the use of fossil fuels as well as the possibility of creating jobs in the areas where the projects are installed. The growth of this type of generation in Brazil has been driven by strong investor interest due to the characteristics of the country's winds, mainly from the Northeast. The winds are strong, stable and most of the time follow the same direction, characteristics that make windfarms in the Northeast region have high levels of capacity factor. By evaluating the data from the wind farms installed in Ceará, it can be observed that they present one of the best capacity factors in Brazil and have values above the world average. This indicates and reinforces the viability of implementing this type of energy generation in the area. It was verified that there are studies about wind conditions but there are no studies that correlate this information with the infrastructure conditions of the State. Therefore, the objective of the present work is to identify the appropriate areas for the allocation and use of wind energy in the State of Ceará through the integration of Geographic Information Systems (GIS) tools and multicriteria analysis for decision making.

Keywords: Windfarms; Renewable energy; Potential for windfarms installation; Process analytical hierarchy.

Resumen

La energía eólica tiene muchas ventajas en comparación con las energías tradicionales, desde la capacidad de reducir el uso de combustibles fósiles hasta la posibilidad de crear empleos en

las áreas donde se instalan los proyectos. El crecimiento de este tipo de generación en Brasil ha sido impulsado por un fuerte interés de los inversores debido a las características de los vientos del país, especialmente del noreste. Los vientos son fuertes, estables y la mayoría de las veces siguen la misma dirección, características que hacen que los parques en la región noreste tengan altos niveles de factor de capacidad. Al evaluar los datos de las granjas eólicas instaladas en Ceará, se puede observar que presentan uno de los mejores factores de capacidad en Brasil y tienen valores superiores a la media mundial. Esto indica y refuerza la viabilidad de la implementación de este tipo de generación de energía en la zona. Se verificó que existen estudios sobre las condiciones de los vientos, pero no hay estudios que correlacionen esta información con las condiciones de la infraestructura del Estado. Por lo tanto, el objetivo del presente trabajo es identificar las áreas apropiadas para la asignación y el uso de la energía eólica en el Estado de Ceará a través de la integración de herramientas de Sistemas de Información Geográfica (SIG) y análisis multicriterio para la toma de decisiones.
Palabras clave: Parque eólicos, Energias renovables, Potencial para la instalación de parques eólicos; Jerarquía analítica de procesos.

1. Introduction

Wind energy has been used for thousands of years to produce work, mainly to move boats, to grind grids, through windmills, to pump water, to move sawmills, among other applications. Nowadays, humanity faces a great challenge that is to supply the energy demand preventing aggression to the environment and the insertion of energy generation using clean energy resources has been growing. Wind energy is part of the solution to this problem, and it has many advantages because it is renewable and clean and, if used to replace fossil fuel sources, it helps to reduce the greenhouse effect (Brazil, 2007).

In 2017, Brazil reached a historical milestone and it exceeded the capacity of 10 GW installed in energy generated by the winds, which corresponds to 7% of the total electricity currently consumed in the country (Câmara de Comercialização de Energia Elétrica, 2018).

Despite the numerous advantages, there are also considerable disadvantages. Wind farms can change the landscape of the region where they are installed, as well as they can be located in the routes of the birds that can collide with the equipment. The noise produced by the rotation of the blades and the effect of light scintillation caused by the passage of sunlight through the moving blades can cause discomfort to the community living nearby. Also, the speed of the winds is variable and has intermittent intensity. Since the Industrial Revolution, the countries economic competitiveness and the quality of life of their citizens are intensely influenced by energy consumption. Plan the energy sector in the long term by optimizing economically viable energy resources that have a low environmental impact it is the great challenge for these countries. The way that they conduct this issues in an increasingly globalized market and growing concern about the environment is very important (Tolmasquim, Guerreiro, & Gorini, 2007). And in this context, renewable wind and solar solutions have been gaining space in recent years.

In scientific papers, it is common to find works on renewable resources and their advantages; however, it is necessary to correlate the infrastructure conditions with the wind conditions according to the reality of these areas. Mapping these areas involves the use of a variety of data sources in which weights are assigned to geographical criteria. For this, the use of geographic information system (GIS) associated with multicriteria decision-making analysis techniques is an excellent tool to identify areas with real potential for renewable energy exploration (Almeida, 2018). Several international studies were found following this logic, but for the national territory it was found a reduced number. For the state of Ceara specifically it was found no paper which was possible to analyse wind potential and infrastructure. Therefore, the objective of the present work is to identify the appropriate areas for the use of wind energy in the State of Ceará, correlating infrastructure conditions and wind conditions. This was accomplished through the integration of Geographic Information Systems (GIS) tools and multicriteria analysis for decision making.

2. Theoretical Background

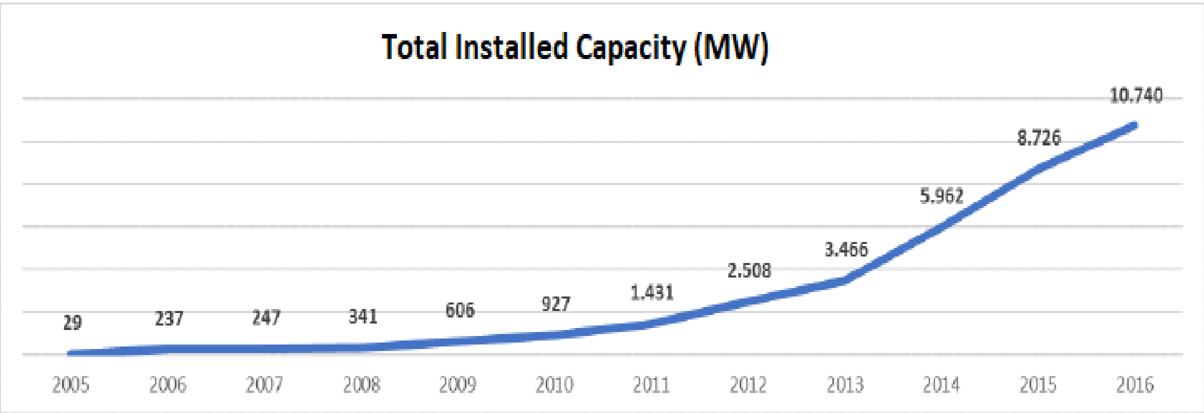
2.1 The importance of wind energy in Brazil

Brazil has a total of 4,920 power plants in operation, which corresponding to 166.67 GW of installed capacity (Agência Nacional de Energia Elétrica, 2017). The transmission network that interconnects the entire system has approximately 135,000 km of transmission lines (Operador Nacional do Sistema Elétrico, 2017a). It can be said that the National Interconnected System (SIN) is hydro-thermo-wind of large size, predominating hydroelectric plants. The four subsystems are interconnected, allowing energy transfers between them, optimizing resources (Operador Nacional do Sistema Elétrico, 2017b). The hydroelectric plants are distributed in several regions of Brazil and have been the main source of electricity generation for several decades, allied to thermoelectric plants in case of hydrological seasonality or high-energy demand.

On the other hand, the main challenge of thermoelectric plants is the impacts due to atmospheric emissions. The entry of wind power plants, although with a variable supply profile, plays an important role in the operational safety of the SIN, as its generation helps in the less using of the reservoirs and the reduction of thermal plants in use in periods of unfavorable hydrology. Also, they still act with some complementarity with hydraulic generation in the dry periods of the years (Tolmasquim, et al., 2007). The installation close to small cargo centers, in the countryside, reduces the losses in transmission and sub-transmission, increases the reliability of the area referring to energy supply and stimulates the use of local resources (Custódio, 2009).

Installed wind capacity is constantly developing in function mainly due to the increase in the use of electric energy in the country which requires the expansion of interconnections to ensure continuity of service to the load. An example of this development is the growth of total installed power and the great entrance of wind farms in the period between January 2014 (2.6 GW) and October 2015 (8.3 GW), whose growth in this period was 177% (Tolmasquim et al., 2007). Figure 1 shows the evolution of wind energy in the country since 2005 to 2016 (Global Wind Energy Council, 2020).

Figure 1: Evolution of installed capacity in Brazil.



Source: Adapted from Global Wind Energy Council, 2020.

2.2 Potential and Capacity Factor of Ceará

A preliminary study conducted by Vestas company and the Federation of Industries of the State of Ceará (FIEC) in 2017pointed preliminary data of the study "Special SiteHunt

Report - The State of Ceará, Brazil" that are summarized in Table 1.

Table 1: Wind speed and capacity.

Wind Velocity	Capacity (GW)
>8,5 m/s	18,9
8,0 – 8,5 m/s	11,1
7,5 – 8,0 m/s	19,0
7,0 – 7,5 m/s	31,2
6,5 – 7,0 m/s	35,8
6,0 – 6,5 m/s	47,7
<6,0 m/s	162,0

Source: Adapted from FIEC, 2017.

According to Custódio (2009), Ministério de Minas e Energias (2007) and Agência Nacional de Energia Elétrica (2017), locations with winds from 7 m/s to 8 m/s are considered good for exploration. For this study, it was considered winds with velocity above 7 m/s.

The Capacity Factor (FC) represents the proportion of energy generated as a function of the installed capacity of the wind farm. Because of the variability and, in some cases, the unpredictability of the wind flow, the total installed capacity in a wind farm is different from the total energy produced by it. The FC represents the proportion of this energy effectively generated as a function of the installed capacity of the wind farm (Melo, 2013).

FC of Brazil has increased over time, as has occurred in the world, as a result of successive increases in the size of the installation, accompanied by technological development, as well as the choice of better areas.

In Germany and China, the FC average is estimated at 20% and in the United States at 33% (Ministério de Minas e Energias, 2007). The world average is around 24% and Brazil has a FC average of 40% to 50%, where the northeastern coast can still reach average values of 60% (Costa, Casotti, & Azevedo, 2009).

The Câmara de Comercialização de Energia Elétrica (CCEE) releases monthly data on the generation of power plants throughout the country. Based on the concept of FC and using the data presented by CCEE, the averages by the state were calculated and are presented in

Table 2, where it is possible to verify that Ceará has one of the best values. In 2014, the report did not contain data from all wind farms, therefore, only the data presented by the agency are shown.

Table 2: Windfarms capacity factors per State.

State	2017	2016	2015	2014	Average
RN	45,6%	45,5%	33,2%	*	41,4%
CE	38,6%	40,6%	40,1%	41,7%	40,3%
BA	45,6%	41,4%	32,0%	42,0%	40,2%
PE	47,8%	46,6%	17,5%	*	37,3%
PI	43,5%	43,4%	14,5%	*	33,8%
RS	38,6%	34,5%	22,2%	*	31,8%
RJ	31,6%	27,8%	31,1%	31,9%	30,6%
PB	30,9%	30,9%	26,6%	28,1%	29,1%
SE	24,3%	20,8%	21,5%	21,6%	22,0%
PR	20,5%	18,1%	19,4%	22,1%	20,0%
SC	13,4%	13,9%	14,7%	22,4%	16,1%

Source: Adapted from Câmara de Comercialização de Energia Elétrica, 2018.

2.3 Steps for the construction of a wind farm

The first step in which the viability of the wind farm implementation is analyzed is the definition of the installation area and the evaluation of the wind potential in this site. Information on wind is obtained through specific studies from topographic maps, monitoring systems to verify the quality of the wind and use of satellite images. This information is considered to establish an average annual velocity and expected energy generation, as well as to study the economic viability of the wind farm implementation (Dutra, 2008).

With the wind potential and area definition, the next step is to design the site layout. For this, it should be defined the type of the wind turbine, manufacturer, the height of towers, electrical power generation, forecast of annual power generation and maximum production capacity. In this step, soil studies and infrastructure for energy supply are also carried out, regarding the distance to the nearest substation and the logistics plan for the distribution of electricity generated (Vale, 2012). The project should also include environmental and socio-economic studies so that the plant has the least possible impact on the region. Besides, the area must be regularized and with the respective valid environmental licenses.

2.4 Geographic Information Systems and Renewable Energies

Geographic Information Systems (GIS) are computer systems where it is possible to store, integrate, manage, analyze, model and display georeferenced data. These systems are capable of integrating various information such as georeferenced maps with images or graphics (Mennecke & Crossland,1996).

The development of GIS has made it possible to incorporate geographic analysis as a new computer variable for model applications for several studies. It allows the evaluation of zoning, proximity, geographical location variables and their connections to the study áreas (Operador Nacional do Sistema Elétrico, 2017b).

One of the main applications of GIS in planning is the assessment of the suitability of areas for a particular purpose (Tomlinson, 2007). For example, evaluation of the use of renewable energy sources (Tiba et al., 2010). As the wind potential is not spatially homogeneous, it is necessary to use tools that relate environmental and structural factors to evaluate site area (Brand, 2016).

2.5 Multicriteria analysis and its use in the evaluation of areas

In 1970, the HPA (Hierarchical Process Analysis) method was developed by Saaty and uses a hierarchical structure of objectives through parity comparisons between the criteria and among the alternatives according to each criterion adopted (Saaty, 1987).

First, decision-makers must define the hierarchical decision matrix, which there should be the purpose of the problem. The matrix must be composed at its first level with the objective, followed by the decision criteria adopted and then by the alternatives, and if there are sub-alternatives. Each phase of the matrix is called the decision level, starting at the top of the matrix (Neves & Figueiredo, 2011).

This method can be applied in several processes involving planning, resource allocation and conflict resolution. In its most general form, it has a nonlinear structure for the realization of both inductive and deductive thinking, considering several factors simultaneously and using numerical excanges to conclude (Saaty, 1987).

The second step consists of the collection of decision-makers' data, or experts, in comparing pairs of alternatives on a qualitative scale, where each value has the relation of importance of this weight to the importance of verbal judgment, that is, the attribution by which the weight must be used (Lima, 2016; Neves & Figueiredo, 2011).

3. Methodology

Methodology is the path to get a research that can be accepted by academic and cientific community as stated by Pereira at al. (2018). In this study, a combined analysis was applied between GIS and AHP method to identify suitable sites for the installation of Wind farms. The exclusion criteria (CE) are presented and used to restrict the inadequate areas and then the AHP method is applied to define the weights and their classification criteria (CC).

3.1 Study Area

The state of Ceará is in the northeast region of Brazil and occupies an area of approximately 148,000 km². The Instituto Brasileiro de Geografia e Estatística (IBGE) estimates that the population of the state in 2017 is 9,020,460 and only in the metropolitan region of Fortaleza there are approximately 4 million inhabitants, corresponding to approximately 44% of the population of the state (Instituto Brasileiro de Geografia e Estatística, 2020).

According to the Instituto de Pesquisa e Estratégia Econômica do Ceará (IPECE), the predominant climate in the state is the warm semiarid tropical occurring in about 68% of its territorial area. This type of climate has characteristics of scarcity and rainfall irregularity associated with high rates of evapotranspiration; these conditions make the state susceptible to the phenomenon of droughts (Instituto de Pesquisa e Estratégia Econômica do Ceará, 2020).

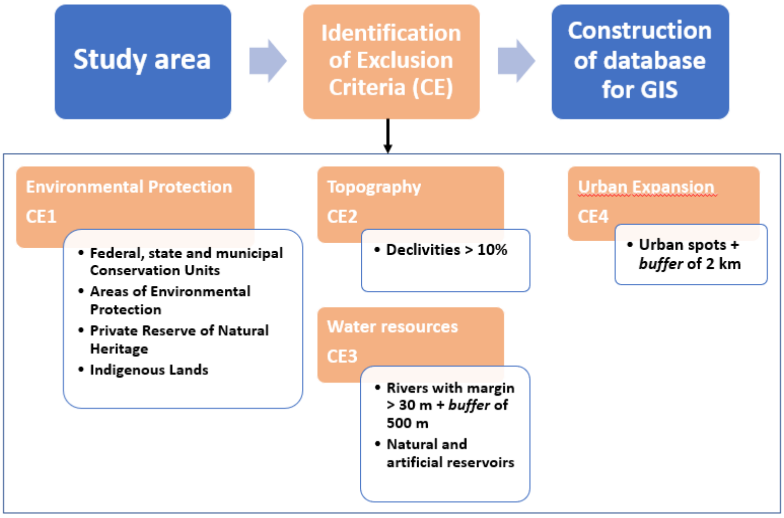
3.2 SIG analysis

The initial step for the analysis is the exclusion of areas that are considered unsuitable for the implementation of large wind farms. Therefore, it was defined what criteria are the restrictive ones that aim to reduce the useful area available for installation of wind farms.

The following exclusion criteria (CE) were used in this research: areas of environmental protection (CE1), topography (CE2), hydric resources (CE3) and urban expansion (CE4). Based on the specialized literature, these are the factors most analyzed to evaluate the wind potential of certain regions.

The following subsections address the relevance of each of these criteria and Figure 2 illustrates the methodological flow used in this step. The software used was ArcGIS (Esri, 2020).

Figure 2: Model for Analysis SIG.



Source: Authors.

3.3 Classification of suitable areas

After the identification of restrictive areas for the installation of wind farms and the exclusion of their areas in the state map, the multicriteria analysis methodology was applied to identify the optimal locations for the installation of these ventures. The classification criteria and their respective levels were identified based on importante literature reviews.

Three classification criteria (CC) were identified: wind speeds (CCI), the distance of accesses roads (CC2), the distance of transmission lines (CC3) and substations (CC4), with the weights shown in Table 3, with 100 being assigned for more efficient characteristic and 0 for more unfavorable.

Table 3: Criteria used in the GIS analysis model.

CC1	Wind Velocity (m\s)	Value	CC2	Access Roads Distance (km)	Value
1	>8,5	100	1	5 – 10	100
2	8,0 – 8,5	95	2	10 – 20	80
3	7,5 – 8,0	90	3	20 – 30	60
4	7,0 – 7,5	85	4	30 – 40	40
5	<7,0	0	5	Mais de 40	0
CC3	**Transmission Lines Distance (km)**	**Value**	**CC4**	**Substation Distance (km)**	**Value**
1	0 – 5	100	1	5 – 10	100
2	5 – 10	80	2	10 – 20	80
3	10 – 15	60	3	20 – 30	60
4	15 – 20	40	4	30 – 40	40
5	10 – 30	20	5	Mais de 40	0
6	30 – 40	10			
7	Mais de 40	5			

Source: Authors.

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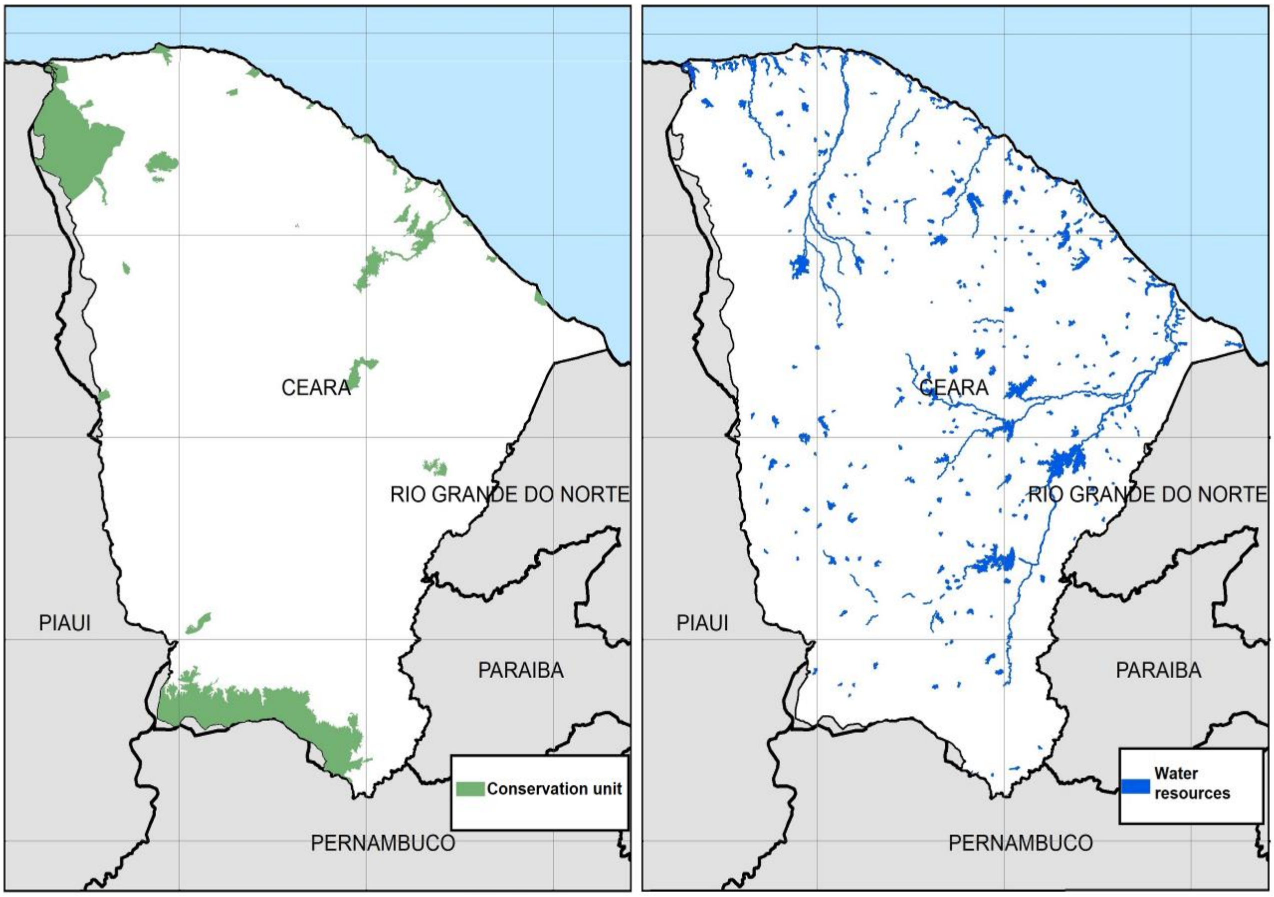
4. Results

4.1 Exclusion Thematic Maps

The state of Ceará has few areas for environmental conservation. Water resources also have a minimal contribution to areas that are unsuitable for wind energy exploration. Estimating the expansion of a city is unfeasible in view of their constant verticalization.

Based on the literature found, for urban centers, areas associated with urban spots and a buffer of 2,000 meters apart were excluded. In the case of topography, areas with slopes higher than 10% were excluded as shown in Figure 3 and Figure 4.

Figure 3: Exclusion maps for areas that are not suitable for the construction of wind farms considering conservation units and water resources.



Source: Authors.

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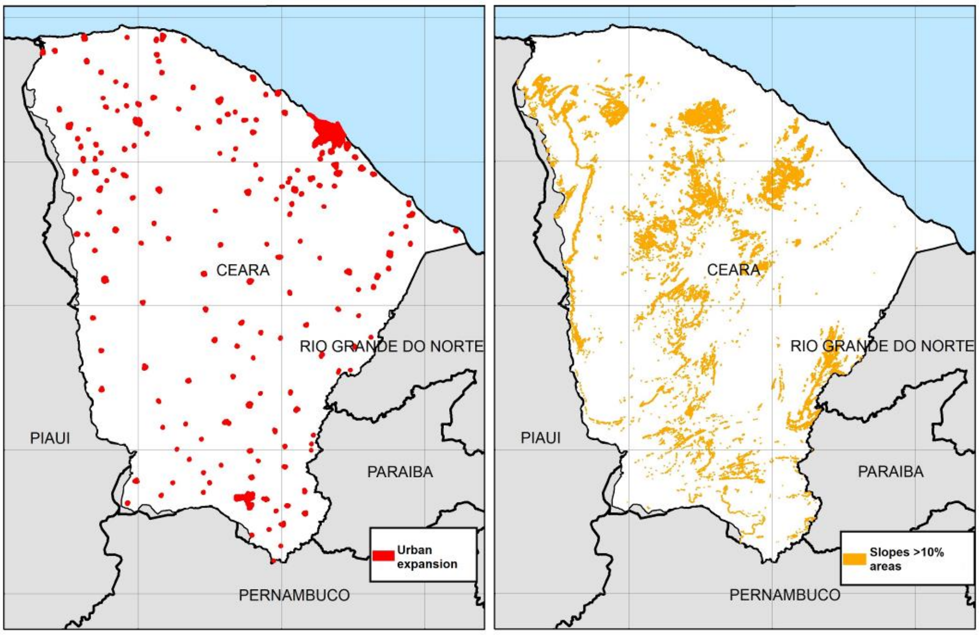
Figure 4: Exclusion maps for areas that are not suitable for the construction of wind farms considering urban areas and sloping land>10%.

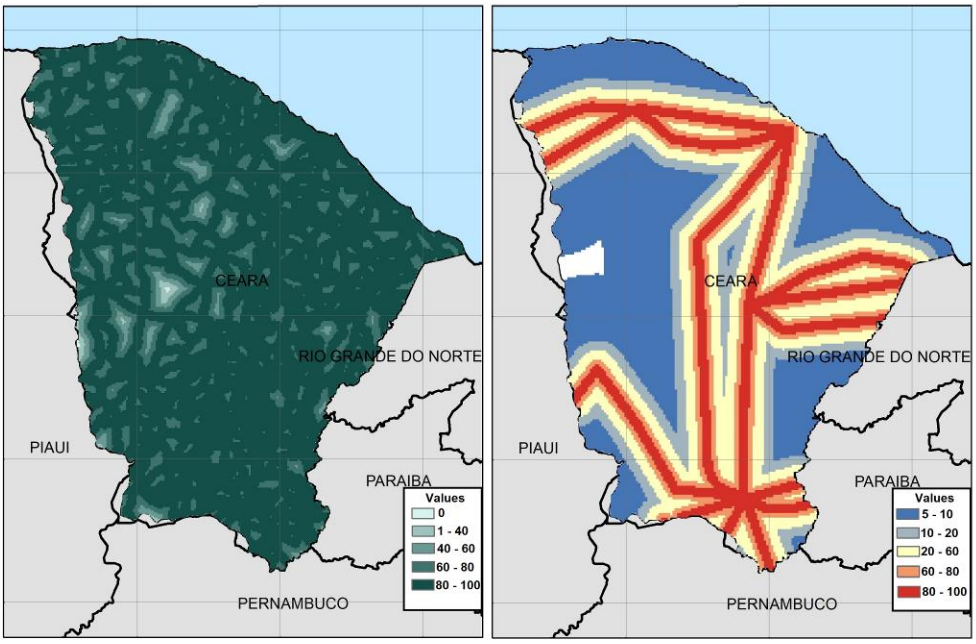


Source: Authors.

4.2 Thematic Classification Maps

As for the classification criteria, it can be observed that the state is well attended quantitatively by the presence of road access as shown in Figure 5.

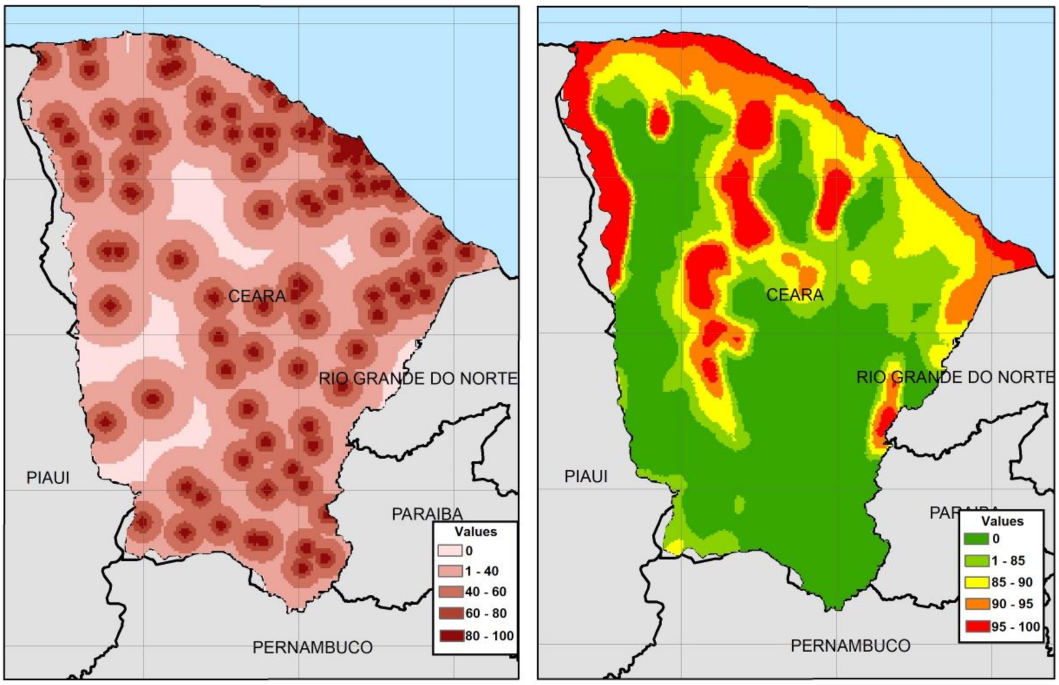
Figure 5: Criteria of classification by access roads (left) and transmission lines (right).



Source: Authors.

Regarding the transmission lines, the availability of transmission is decisive in the viability of the project, given that the need to build large extensions of transmission lines and substations increases the cost of the project and can make it unattractive (Custódio, 2009).
By analyzing the data applied to the grid, it can be observed that the main obstacle to Ceará's energy infrastructure lies in the location of the transmission lines since large portions of the state are more than 40 km from the networks. For substations, the situation is less critical than that of lines, there are only small isolated portions, as shown in Figure 6.

Figure 6: Criteria of classification by location of substations (left) and speed of the winds to 100 m of height (right).



Source: Authors.

The map on the right in Figure 6 demonstrates the criteria for the occurrence of suitable wind speeds. It can be observed that areas with the three highest classification values (from 7.5-8.0 m/s, 8.0-8.5 m/s and greater than 8.5 m/s) are areas on the coast.

4.3 Zoning map for the installation of wind farms

The areas were classified according to the influence of the classification variables: more adequate, adequate, moderately adequate, slightly adequate, less adequate and inadequate, as shown in Figure 7. The first three types correspond to approximately 62% of the total area of the state, divided in the proportion of Table 4 are the indicated areas for

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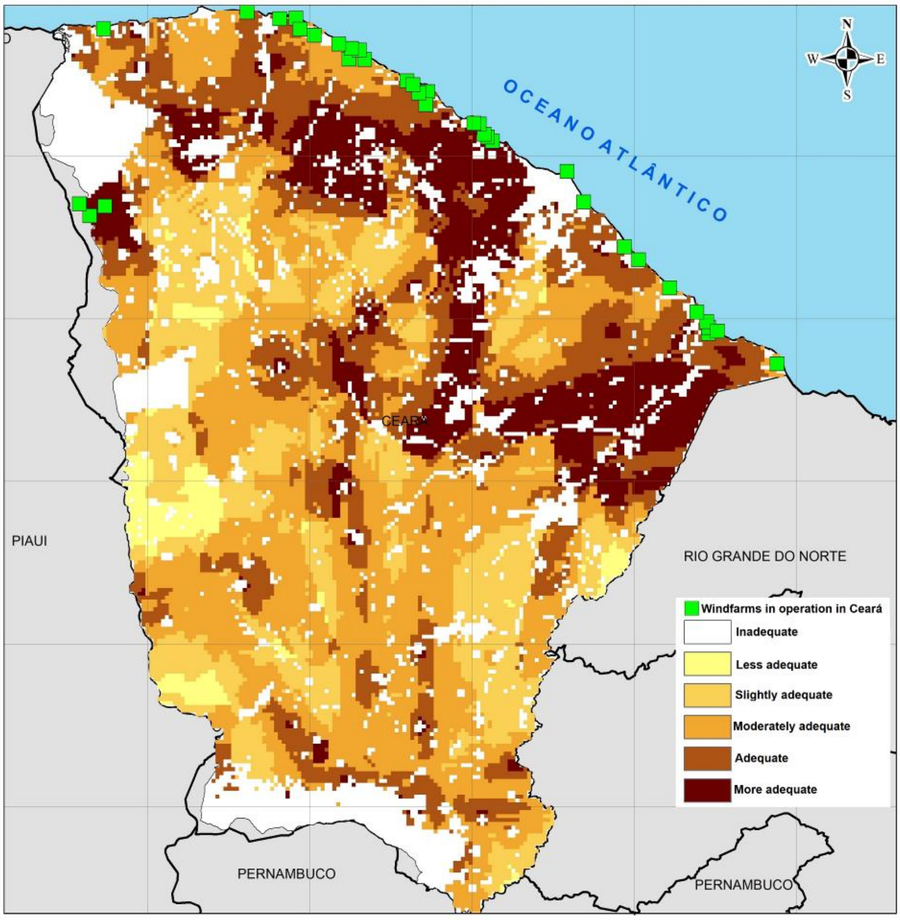
implantation of the wind farms.

Figure 7: Areas by classification.



Source: Authors.

Table 4: Areas of the state by classification.

Classification	Areas (km²)	Areas (%)
Moderately appropriate	45.543,88	31%
Appropriate	27.825,25	19%
More appropriate	19.453,74	13%

Source: Authors.

5. Conclusion

The use of multicriteria analysis with a Geographic Information System was presented as an efficient tool to locate areas with potential for the installation of wind farms. Based on the data obtained in this paper, Ceará presented a relatively high potential for the installation of these energy plants, indicating that 62% of its area is suitable. The research identified four exclusion criteria (areas of environmental protection, topography, water resources and urban centers) to delineate inappropriate areas.

Four criteria were identified for the areas classification: wind speeds, distance of highways, distance of transmission lines and distance of substations. Then, the AHP method was applied and, as a result, it was identified that the state has an area of 92,822.87 km² that are between moderate and more adequate. The areas with the highest wind speeds are located in the coast and mountain regions and it has been seen that one of the obstacles is the supply of transmission line for the flow of the energy generated. However, according to the Operador Nacional do Sistema Elétrico (ONS), there are plans to build transmission lines that are estimated to be completed in 2019, 2021 and 2022.

The growing participation of wind generation in the Brazilian electric power matrix will require strong structural solutions in the basic energy system to allow the flow of all production. Therefore, it is up to the public sector to carry out efficient medium- and long-term planning and also to attract private sector investments.

The wind farms in operation in Ceará have the second largest capacity factor of the ones installed in Brazil. Although the current sites are mostly concentrated in the coastal region, this paper shows that is possible to explore other areas. The state already has the natural factor of intensity of the winds presenting exceptional conditions for the generation of wind energy: constant, well directed and high winds and well distributed in the geographic area. It is necessary, therefore, to create a favorable environment so that the attractiveness of the state can be rescued so that investments will occur again.

On the one hand, public sectors must carry out effective medium and long-term planning. Partnerships such as the Port of Rotterdam and the privatization of Pinto Martins International Airport in the State are factors that can influence the outcome of energy auctions and the allocation of resources within the state and, consequently, attracting the entire industrial production chain, generating income, jobs and contributing to the diversification of the energy matrix and sustainable development.

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Daniela Cadore Vale – 60%

Renato Sipelli Silva – 25%

Erika da Justa Teixeira Rocha – 5%

Auzuir Ripardo de Alexandria – 10%