A MULTICRITERIA GIS-BASED APPROACH FOR SITING WIND FACILITIES IN BRAZIL

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Overview
This paper presents a methodology for evaluating and selecting appropriate sites for wind farm development at the regional level. In Brazil, the state of Rio Grande do Norte is known for its strong and stabilized trade winds. Despite these favorable climatic conditions, economic, social and environmental factors also have important roles in the planning of large-scale wind projects. This study aims to incorporate various siting variables using geographic information systems (GIS) and a spatial multi-criteria decision analysis in order to identify suitable sites for wind farm installation. Furthermore, the decision model is used to appraise the suitability of already licensed and operating projects. The results of this paper aim to provide a more integrated and spatially informed approach to assist the decision-making behind utility-scale renewable energy facilities.

Keywords – GIS; Wind farm siting; Spatial Analysis; Renewable energy

1. Introduction

Wind energy is the fastest-growing source of electricity in the world, reaching a global installed capacity of 487 GW in 2015 (IRENA, 2016). In Brazil, public policies and changes to the regulatory framework have made wind power a priority within long-term supply planning. When it comes to the topic of diversifying the energy sector, industry stakeholders generally agree that wind is an ideal alternative form of energy that should be promoted. This is due to its ability to complement the underlying hydropower base and contribute to supply reliability (Cunha, et al., 2012). For critics of large hydroelectric plants, wind represents a way of reducing dependence on hydropower within the traditional system of centralized generation. The country is currently ranked 9th globally in terms of installed capacity, where wind accounts for 6.3 percent of the Brazilian energy matrix (ANEEL, 20017).

The favorable wind resources in the Northern and Northeastern states have attracted most of the public and private investments. The region’s stabilized trade winds are accelerated by a semi-stationary high-pressure center over the Atlantic. For project developers, these physical features translate into increased productivity and higher returns. The practice of leasing the properties of poor landholders to build wind parks can present an additional source of income generation, further grounding the positive externalities of wind power.

Where this agreement usually ends, however, is on the negative impacts associated with wind deployment. One of the major technical challenges to wind energy development is the need to

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locate areas that support the economic and social viability of wind projects. For instance, in Brazil, the lack of access to grid connections has delayed the operation of wind farms, resulting in severe bottlenecks and ultimately dampening sectoral growth. Furthermore, environmental impacts caused by wind farms, which are often located on sand dunes and other coastal systems in the Northeast, can create conflicts between wind developers and local communities. Consequently, these factors can impose practical constraints on project planning while undermining the sustainability claims of wind as an environmentally-friendly source of energy.

Suitability mapping using Geographic Information Systems (GIS) has the potential to assist in the decision-making process when designing and implementing wind projects. A multicriteria decision-making (MCDM) analysis can combine a variety of spatial data in a meaningful way, where a weighting scheme emphasizes the relative importance of one criterion to another (Janke, 2010). The application of GIS multicriteria modeling for energy planning, which acknowledges the complex nature of satisfying multiple economic, social, and environmental objectives when considering traditional and alternative energy sources, is thus underpinned by an integrated resources planning (IRP) approach (Jannuzzi & Swisher, 1997). An essential aspect of the IRP perspective, which differs from other strategies for supply planning, is that societal costs must be included, such as the mitigation of environmental impacts engendered by certain resource choices.

The broad literature on siting wind and renewable energy facilities reveals several criteria that define suitable areas for development. These factors include proximity to key infrastructure such as roads and the existing grid system, winds speeds, avoiding urban areas and lands designated for conservation, as well as modifying turbine operations in light of the migratory patterns of birds and other wildlife (Baban & Perry, 2001; Janke, 2010; Latinopoulos & Kechagia, 2015). Several studies focusing on northeast Brazil have documented specific instances of social and environmental conflicts resulting from wind farm implementation. They tend to highlight the socio-environmental consequences that can make Brazil's wind development unsustainable, such as the construction of wind farms on unstable sand dunes, the disruption of river and lake systems, and the alteration of vegetation, all of which can affect the livelihoods of local communities and foment opposition (Gorayeb & Brannstrom, 2016; Brannstrom, et al., 2017).

Despite the growing importance of the Brazilian wind industry, no GIS-MCDM study exists which addresses the varied dimensions of selecting domestic wind farm locations. GIS-based decision support models which focus on the Brazilian context tend to rely on wind potential as the main criterion that defines exemplary areas (da Silva Machado Copque, et al, 2013; Tilba et al., 2010; Vicari, 2012). Socio-economic and environmental criteria which also influence the wind implementation process are not incorporated in an analytical way.

This paper develops a modeling framework to determine suitable locations for wind farm development at the regional level. The objective of this spatial analysis is twofold. Using a framework employed by Latinopoulos and Kechagia (2015), this spatial decision model can serve as a tool for an ex-ante evaluation of optimal locations for future projects, taking into consideration several planning and environmental criteria. On the other hand, it can be used to evaluate ex-post the appropriateness and suitability of already licensed or operating projects. This process can provide useful insights into: (a) the relative importance of the factors that currently impact regional wind planning, as well as (b) the overall suitability of pre-existing projects (Latinopoulos & Kechagia, 2015, p.552).
2. Study Area

Rio Grande do Norte, a state situated in the Northeastern region of Brazil, was selected as the study area. The state has a population of approximately 3,442,175 and the capital and largest city is Natal. The state has the largest number of wind farms with 111 generators in operation which produced 3,667 MW in 2016. The coast of Rio Grande do Norte has an average annual wind potential at height 50 m of 7.0 m/s. Although the state has a high wind energy potential, it was prohibited by the Brazilian government from participating in recent energy auctions because of delays in building transmission lines, along with the states of Bahia, Ceará, and Rio Grande do Sul.

The main reason for selecting this area is because it exemplifies a common problem for wind development: the harnessing of favorable climatic conditions has been impeded by other technological and social factors. The role of Rio Grande do Norte as a major supporter of wind power in Brazil further makes it a particularly useful case study for our ex-post analysis. The methodology developed in this paper is applied to evaluate the suitability of the state’s pre-existing wind farms already in operation. The argument can also be made that, as more renewable energy projects are promoted, viable land will become the key constraint, confirming that appropriate site selection will become paramount for the future development of onshore wind farms (Grassi, Chokani, & Anhari, 2012; Watson & Hudson, 2015). Figure 1 displays a map of the study area.

![Figure 1 - Location of major roads and transmission lines in Rio Grande do Norte](image-url)
3. Methodology

The selection of sites for wind farm installation is based on a number of technological, economic, social, and environmental factors – also known as siting criteria. The suitability analysis aims to identify the most appropriate sites for project development while minimizing, or even eliminating, environmental or social restrictions to wind power development. The overall procedure uses spatially referenced data to create a decision map of suitable locations. A multicriteria analysis in a raster data model was chosen because it allows trade-offs among variables: a low score on one criterion can be offset by a high score on another (Latinopoulos & Kechagia, 2015, p.550). All map layers have to thus first be converted from vector to grid-based data.

In the first step we exclude infeasible sites, which represent our known planning constraints, using individual exclusion layers based on Boolean true/false logic. In part two, we select our evaluation variables which are used to generate a set of layers for each criterion. We then calculate a composite suitability index and the associated parcels that demonstrate ideal areas for development, as defined by our model. This suitability index is then applied ex-post to evaluate operating wind sites.

The following mathematical expression was used as our multi-criteria decision-making (MCDM) model. It defines our suitability areas as the sum of our weighted criteria multiplied by the product of our restrictions, where $S$ is the suitability for a wind facility site, $w_i$ is the relative importance (weight) of factor $i$ ($i=1,\ldots,5$), $C_i$ is the suitability criteria, and $r_j$ is the restriction for factor $j$ ($j=1,\ldots,3$):

$$S = \sum_{i=1}^{n} w_i C_i \prod_{j=1}^{m} r_j$$

Eq. (1)

The following georeferenced variables were obtained from available geospatial databases: Wind speeds, cities, areas designated for environmental conservation or protection, slope, and the locations of roads and transmission lines. Wind speed GIS data was obtained from the Center for Electricity Research (Cepel). The data are based on annual wind speed averages measured at 50 m above the ground and produced in MesoMap for 360 days, extracted over a period of 15 years. The days were chosen by means of random sampling at several heights. Point locations are organized into 10 km by 10 km cells.

Using ArcGIS 10.5, the point values of wind speeds were interpolated using the inverse distance weighting (IDW) interpolation method to estimate a spatially continuous surface for wind speeds. This method creates intermediate values for areas without data within the range of the given inputs. While a reasonable prediction map was produced, a noted downside to this interpolation application is that the predicted values of higher wind speeds near the coastline were allocated less area due to edge effects. This is inconsistent with reality, where high velocity wind speeds should occupy more area on the coast.
3.1. Exclusion of infeasible sites

During the first step, we identify areas to be excluded where constraints are not met. Therefore, we expand our previous equation for three restrictions to determine the wind farm exclusion zones. As a result, Eq. (1) becomes:

$$ S = \sum_{i=1}^{n} w_i C_i (r_1 \cdot r_2 \cdot r_3) $$

Eq. (2)

The three constraint criteria are summarized in Table 1. The following reasoning was applied:

- In physical terms, wind farms should be located on sites with high wind velocities. The average wind speed is a crucial factor for creating the necessary mechanical energy that determines the economic viability of wind farm projects. In this context, the prediction map of interpolated wind speeds was used, and areas with average wind speeds of less than 5 m/s were excluded (Restriction R1).

- To minimize the impacts on livelihoods and standard of living of human settlements, wind farms should be located at least 1000 m from cities and urban areas (Restriction R2). The social implications of wind farms include visual impacts and the level of sound or noise produced by wind turbines. Studies also cite the negative impacts on the livelihoods of traditional communities, as well as on urban growth and expansion (Brannstrom, *ibid*; Larissa, 2014).

- To preserve the environment, wind farms should not be built on or within 500 m of areas that have been designated by public bodies for environmental protection (Restriction R3). Areas of environmental protection included municipal, state, and federal Units of Conservation (UCs) as administrated by the Ministry of the Environment (MMA), and Geoparks and Geosites form the Brazilian Geological Survey (CPRM).

Table 1
Description of constraints criteria.

<table>
<thead>
<tr>
<th>Restriction</th>
<th>Buffer zones/exclusion zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$ Wind potential</td>
<td>Areas where average wind speed is less than 5 m/s</td>
</tr>
<tr>
<td>$r_2$ Distance to cities</td>
<td>1000 m</td>
</tr>
<tr>
<td>$r_3$ Environmental protection</td>
<td>500 m</td>
</tr>
<tr>
<td>and conservation areas</td>
<td></td>
</tr>
</tbody>
</table>

Map layers were converted from vector to grid-based data model and represent the restrictions to develop wind parks. Boolean intersection operations, using the logical “AND” were applied to all constraint areas (0 = unacceptable site, 1 = acceptable site). Figure 2 illustrates the outcome of this procedure, showing the excluded zones and the potential sites for wind development.
3.2 Evaluation criteria

In the next step of the analysis, we focus on the suitability layer using the five factors that we have identified and their associated weights. Therefore, returning to Eq. (1), we expand our formula:

$$S = (w_1C_1 \cdot w_2C_2 \cdot w_3C_3 \cdot w_4C_4 \cdot w_5C_5) \prod_{j=1}^{m} r_j$$

Eq. (3)

Table 2
Description of the evaluation criteria (factors) used for wind site selection.

<table>
<thead>
<tr>
<th>Weight ($w_i$)</th>
<th>Criterion</th>
<th>Policy Relevance</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>Wind Speed</td>
<td>Technical/Economic</td>
<td>Benefit</td>
</tr>
<tr>
<td>$C_2$</td>
<td>Distance from cities and transmission lines</td>
<td>Technical/Economic</td>
<td>Cost</td>
</tr>
<tr>
<td>$C_3$</td>
<td>Distance from road network</td>
<td>Economic</td>
<td>Cost</td>
</tr>
<tr>
<td>$C_4$</td>
<td>Outside of avian conservation area</td>
<td>Environmental</td>
<td>Benefit</td>
</tr>
<tr>
<td>$C_5$</td>
<td>Slope</td>
<td>Technical/Economic</td>
<td>Cost</td>
</tr>
</tbody>
</table>

Unlike the restriction criteria, which are expressed in Boolean form and are intended to rule out areas for development, evaluation criteria are typically measured on a continuous scale and have the aim to enhance or detract from the suitability of alternative locations. There are two types of factors: (a) benefit criteria which contribute positively to site selection and (b) cost criteria which contribute negatively to site selection where, in this latter case, lower values are more preferable than higher ones (Latinopoulos & Kechagia, 2015, p. 555). The raster grids were reclassified...
Figure 3 – GIS variable inputs to model ideal locations for wind farms

using an evaluation scale from 1-10 with steps of 1 to represent the range of suitability for each criterion. The rating scores for each layer’s reclassification map are shown in Figure 3.

The chosen evaluation criteria are not necessarily different from the restrictions. For example, a restriction \( r_1 \) was used to exclude all sites with average annual wind speeds of 5 m/s and lower, as it was considered that the economic feasibility of those sites would be too low. The Boolean approach therefore models a decision-making rule based on the concept that these areas would be excluded entirely from the planning process. In contrast, the evaluation step of the analysis allows for the fine-tuning of the decision maker’s choices by granting higher weights to higher preferences. Therefore, higher weights are given to faster wind speeds. Also, unlike the
Boolean approach, poor performance in one criterion can be compensated by good performance in another.

In addition to wind speed, transmission line vector files were obtained from The Brazilian Electricity Regulatory Agency (Aneel) and urban boundaries from the Brazilian Institute for Geography and Statistics (IBGE). Proximity to transmission lines and urban areas were defined as positive evaluation criteria, since wind parks supply electricity to nearby communities or to an electricity grid to transmit electricity to load centers. Since wind parks can exist near cities and transmission lines, a single raster grid was created to extract the minimum distance of a wind park from an urban boundary or a transmission line. Distance to roads was also scaled in a decreasingly linear way, so that a closer distance would mean a more optimal score. Road vector files were obtained from the National Department of Infrastructure and Transportation (DNIT).

Furthermore, wind farms should ideally be located outside of areas that aim to protect certain bird species. Poorly sited wind farms can have negative effects on bird populations or their habitats. Priority areas for the protection of bird species were downloaded from the MMA database, which is part of a broader database on biodiversity. The areas prioritized for bird conservation were scaled at 1 while areas outside of this area were scaled at 10.

Finally, raster data of slope values were downloaded from the Brazilian Institute for Spatial Research (INPE) Topodata database. The data are organized by 1 degree latitude by 1.5 degrees longitude grid cells at 1:250,000 resolution. Higher inclinations were given less value, with the reasoning being that it would be more difficult and economically costly to construct and provide maintenance for wind parks at higher altitudes.

### 3.3 Multicriteria decision-making and site selection

The multicriteria decision rules are introduced in order to define a relationship between the input maps and the final output map. In this context, our selected factors should be aggregated using spatial multicriteria decision-making, so that an overall Suitability Map (S) will be generated. The objective of this final step in the procedure is to associate each grid cell with a composite degree of satisfaction for the wind farm site selection, and to locate the priority sites in the study area. The weighted linear combination method (Eq. 1) was selected for the multicriteria evaluation. The estimation of weight factors were heuristically defined based on review of the literature (Table 2), rather than more structured techniques for assigning weights, such as Analytic Hierarchy Process (AHP) (Saaty, 1980).

### 4. Results

According to the multicriteria GIS wind model, wind farms should be located in northeastern Rio Grande do Norte and the middle of the state (Fig. 4). These areas are located in the regions with more urbanized areas, which could mean greater access to transmission lines and urban areas to supply electricity. A cluster of higher scores also exists along the northern coastline. We might expect the scores in this cluster to be higher if we had not included the protection of bird populations in our evaluation criteria.
4.1 Ex-post evaluation of current wind farm locations

The main objective of the ex-post evaluation process is to consider whether our rationale for wind site selection can effectively assess the appropriateness of pre-existing wind farms. We do this by using our suitability scores to evaluate wind parks already in operation. In this context, Fig. 4 visually demonstrates the locations of current wind park sites mapped with our suitable areas for wind farm development.

According to the GIS model, wind scores greater than or equal to 80% indicate favorable sites for wind farm development. Five wind parks have a score of 0, meaning they are located within areas restricted from the decision-making process as a result of creating our exclusion layer. They are either a) located within the administrative boundaries of a municipality, or b) within an environmental protection area. However, it is noteworthy that only a small fraction of operating sites (less than 10%) has a suitability score of less than 60% (see Table 3 below). Therefore, it can be generally concluded that the locations of projects are acceptable with respect to this paper’s methodology.

Table 3
Descriptive statistics for the suitability scores of operating wind parks

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>411</td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td>7.420925</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.259688</td>
</tr>
<tr>
<td><strong>Range of Suitability Scores</strong></td>
<td></td>
</tr>
<tr>
<td>$S \leq 60%$</td>
<td>9.98%</td>
</tr>
<tr>
<td>$60% &lt; S &lt; 80%$</td>
<td>41.32%</td>
</tr>
<tr>
<td>$S \geq 80%$</td>
<td>48.70%</td>
</tr>
</tbody>
</table>
4.2 Multicriteria GIS model limitations

A few limitations exist in this study. One is the method of selecting weights for our evaluation criteria. In an ideal setting, the weighting priority would be informed by collaborating with managers, research specialists, and interest groups to enhance the decision-making process (Janke, 2010; Malczewski & Rinner, 2015). In lieu of stakeholder inputs, an Analytic Hierarchy Process (AHP) could also be applied to generate multiple scenarios based on different weighting preferences. For example, in their approach, Latinopaulos and Kechagia (2015. P. 557) present three scenarios to depict different policy orientations which emphasize environmental and social criteria, or technical and economic criteria. It is expected that policy orientation also plays a crucial role in the final ranking of the most suitable areas within our study area, and these aspects could be explored in more depth.

In addition, the aim of this paper is to provide a generalizable methodology for siting renewable energy facilities. However, the variables incorporated are arguably specific to the wind sector and other capital-intensive projects. The emphasis on being close to existing road and infrastructure networks, while relevant for the development of other centralized energy sources, is particularly true for wind farms which require transporting and installing large concrete, steel, and aluminum components. This model also does not take into consideration the broader physical effects of wind towers, such as wake effects.

Conclusions

The environmental and social impacts caused by wind developments depend on the location of the development, where careful design and appropriate site selection can mitigate the associated negative impacts. The Brazilian wind sector is one such example in which the wind sector been challenged by several planning issues. These factors can undermine the sustainability claims of the wind industry while imposing practical constraints on project implementation.

The aim of this paper was to provide an approach to enhance the decision-making process underlying supply planning when promoting alternative energy sources. Drawing on data available from Brazilian planning and energy agencies, a spatial model using geographic information systems (GIS) was developed to demonstrate ideal locations for wind farm development. The state of Rio Grande do Norte was used as a case study to develop and apply this model. The results indicate that the model is capable of identifying locations highly suited for wind farm development, as well as evaluating the appropriateness and suitability of projects in operation. This spatial model developed can be used to assist in the decision-making process when evaluating areas for renewable energy development.
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**Databases**


