

Analysis and selection of optimal sites for wind farms: case study, region north of Mexico

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RESUMEN

El proceso de análisis jerárquico permitió establecer un modelo jerárquico de función objetivo con un conjunto de criterios, con la finalidad de seleccionar los mejores sitios para la instalación de un parque eólico en la región norte de México. En este estudio se utilizó un gran número de criterios conocidos y estimados de distintos tipos (técnicos, económicos, ambientales y sociales) basados en estudios e información preliminar. Dichos criterios permitieron identificar las variables de mayor importancia. El proceso simplifica un problema complejo dividiéndolo en procesos más simples que pueden analizarse de forma independiente, facilitando así la labor de los encargados de la toma de decisiones, ya que permiten contemplar alternativas viables. Obtenidas las variables de mayor peso e importancia para el estudio se transformó cada una de ellas en mapas de factibilidad. Luego, mediante la técnica de álgebra de mapas acoplada a un sistema de información geográfica se evaluaron los sitios (en porcentajes de factibilidad) en un mapa general que cumple con el conjunto de las variables impuestas. Los mejores escenarios para la ubicación de un parque eólico se localizaron en la parte sur del estado de Coahuila. Los análisis de criterios múltiples enfocados a la toma de decisiones en el proceso de planeación y caracterización de sitios factibles de un parque eólico, son herramientas que optimizan la selección de distintas variables favoreciendo las más importantes del proyecto, al permitir que se tomen en cuenta elementos de decisión difíciles de evaluar o cuantificar.

ABSTRACT

The analytic hierarchy analysis process allowed establishing a hierarchical model of a target function under a set of criteria aimed at choosing the best sites for the installation of wind farms in the north of Mexico. In this study, a large number of known and estimated criteria of diverse types (technical, economic, environmental, and social) were used, based on preliminary studies and information that allowed for the identification of the most relevant variables. The process simplifies a complex problem into simpler ones that can be analyzed independently, facilitating the efforts of decision takers since it allows envisaging the feasible alternatives. Once the most weighty and relevant variables were obtained, each variable was transformed into feasibility maps, and through the technique of map algebra coupled to a geographic information system, the sites were assessed in feasibility percentages in a general map fulfilling the set of imposed variables. The best scenarios for the location of a wind farm corresponded to the southern part of the state of Coahuila. The multicriteria analyses focused on decision-making within the planning process and characterization of feasible sites for a wind farm, are tools that optimize the selection of different variables, favoring the most relevant for the project by considering decision elements that are difficult to assess or quantify.

Keywords: hierarchical analysis, multicriteria analysis, optimization, wind farm, geographic information system.

1. Introduction

In Mexico, the growing concern to choose efficient energetic sources with low environmental impact is fostering the development and application of renewable energies; in particular, the installation of wind farms to generate electricity. This type of installations complies with policies of energetic diversification and the reduction of CO₂ emissions proposed by international agencies and supported by the Mexican government, as they reduce the dependence on traditional energy sources and limit their negative effect on the environment (SENER, 2013).

The techniques used to select sites for a wind farm consider two essential factors: the strength of the wind (from 5 m/s on), and the favorable conditions of the site, like access roads and being close to an electrical substation (Serrano et al., 2011). The sites frequently chosen are determined through a cartographic review of the natural resources of the region. Afterwards, a wind speed measuring station is installed which verifies the intensity and direction (collecting data during 12 months). Finally, software (like WAsP) is used, which evaluates the wind resource and calculates the energetic yield of the wind turbines, as well as WindPRO, which analyzes the design and planning of the wind farm, or WindFarm, which optimizes the increase of energy or the reduction of energy costs (Miranda, 2008; Artillo, 2017).

However, more complete studies have been developed that use computational algorithms and mathematical models for selecting the criteria to choose sites and design wind farms (Grady et al., 2005; Herrera et al., 2011, Guzmán, 2017; Konstantinos et al., 2019). Other studies have focused mainly on technical-economic factors to strengthen the decision making about this type of projects, as well as their profitability. In this sense, some analyses add complexity by including environmental and social characteristics as viability criteria in the design and construction of the wind farm. The latter has led to the search and use of better computation techniques that will facilitate the exploitation of this type of renewable energy, considering the economic profitability of the project and its contribution to the social development of communities (Berumen and Llamazares, 2007).

In recent years, methodologies considering multi-disciplinary analyses have been incorporated to eolic projects, particularly in issues regarding site selections and performance optimization (Falces, 2015). Different studies have been carried out to determine the possibility of eolic energy by means of computational mathematic models and multicriteria analyses. Fernández-Jiménez et al. (2009) propose the use of genetic algorithms combined with a geographical information system (GIS) for the selection of wind turbines inside the wind farm. Herrera et al. (2011) describe an optimization model of the technical configurations of a wind farm, using algorithms to maximize the conditions of the proposed project.

This study includes and analyzes technical, economic, environmental, and social criteria that are involved in the planning of a wind farm. Since these studies are performed in stages, generally they are scarcely analyzed, and sometimes many criteria are not included (SEMARNAT, 2002). The environmental and social aspects of eolic projects should have the same or greater relevance than the techno-economic conditions, because the project impacts the former in a more significant way. Therefore, this study is aimed at giving a more specific weight to environmental and social conditions in the selection of recommended sites for wind farms. It proposes to assess the potential of the northern region of Mexico to implement wind farms, elaborating a repeatable methodology that will allow assessing the selected criteria and the territorial conditions, using the instrumental methods provided by multicriteria evaluation and GIS.

When selecting sites for wind farms, the most important geographical, ecological, and social criteria for the region must be included in addition to particular criteria like wind power and access roads, as usually done in the development of this type of project (Zárate and Fraga, 2016). In this study we used computational models and algorithms in order to consider issues of multiple criteria (variables) related to decision making that might function as alternative tools for renewable energy projects, in particular for wind farms. The choice of optimal sites for installing wind farms will lead to adequate and beneficial solutions for project developers, the environment, and the local community.

This study initially proposed a regional area of interest, considering the states along the northern

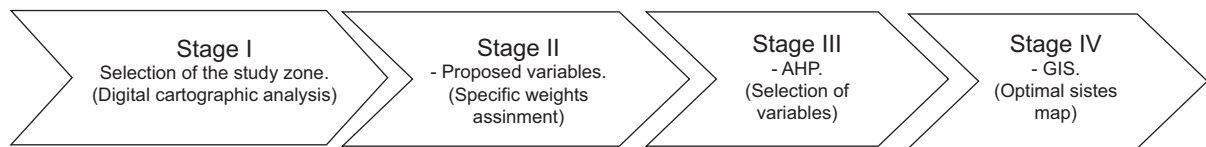


Fig. 1. Flow chart of the proposed methodology.

border (Baja California Norte, Sonora, Chihuahua, Coahuila, Durango, Nuevo León, and Tamaulipas). Traditionally, the development of eolic installations has been concentrated in central and southern regions of the country, mainly in the state of Oaxaca. Over the last years, due to its characterization as an exploitable region, northern Mexico has been taken into account to explore its possibilities for the development of eolic energy, with the expectation of generating large economic and environmental benefits (SENER, 2016).

2. Methodology

The process to select optimal sites for the installation of eolic parks was developed in four stages (Fig. 1): (1) selection of the study zone, (2) statement of variables with their specific weights, (3) analytic hierarchy process to obtain the variables with the greatest relevance, and (4) use of GIS to visualize results.

The methodology requires to determine the study zone based on the digital cartographic information. In addition, a larger period than normal was considered for the measurement of the wind factor, By means of the meteorological model Weather Research and Forecasting (WRF) daily data on direction and amount were analyzed for a period of five years, from 2008 to 2012 (CCA, 2016).

To analyze the variables proposed in this study, we used multiple-criteria decision analysis (MCDA), which helps to make decisions on a posed issue for choosing, classifying, and organizing the proposed elements. Specifically, we applied the analytic hierarchy process (AHP), a powerful and flexible tool for MCDA which is used for issues that require assessing both quantitative and qualitative aspects through a common scale, performing pairwise comparisons between criteria and alternatives. Results were coupled in a GIS, aimed at obtaining a feasibility map of the best sites for the localization of wind farms.

2.1. Selection of the study area

Although in Mexico the development of wind farms has been mainly carried out in the south (as in the aforementioned case of Oaxaca) due to the strength of winds in the region, in recent years the federal government has decided to explore the potential of other non-coastal states of the northern border to take advantage of their wind power resources (SENER, 2016). For this, a series of criteria and restrictions were applied (Table I) using digital cartography and applying maps algebra with GIS. Maps algebra allowed combining different layers of territorial conditions aimed at obtaining alternative information maps connected to aptitudes and/or concrete aspects of the studied area.

According to the characteristics of the study, a grid was designed to subdivide the region and incorporate in each of them the information on the considered variables. The size of the mesh must be according to the information and obtained criteria, and, above all, on the dimensions of the wind farm project. Each cell of this mesh represents a matrix of the possible sites for the installation of wind farms, which eased the interpretation and localization of the data proposed in the study.

2.2 Proposed variables

Both qualitative and quantitative criteria that can influence an eolic project—site variables—were named. In this study, a total of 28 variables divided in four groups were considered (Table II). The proposed criteria for the selection of the most feasible sites were grouped in technical, economic, environmental, and social variables, posing seven conditions for each group. Saaty (2003) establishes this as a necessary condition to avoid confusion and inconsistency in the information by including more than this number of variables.

The proposed variables must allow taking into account the most important aspects of an eolic project, considering its impact on the economy, environment,

Table I. Criteria and restrictions used to delimit the study zone.

Criteria	Apply	Digital cartographic information	Source
1. Northern states of Mexico	YES	States and municipalities	INEGI, 2014
2. Limits of physiographic sub-provinces	YES	Physiographic sub-provinces	INEGI, 2014
3. Coastal states	NO	States of the country	INEGI, 2014
4. Limits with natural protected areas and conservation zones	NO	NPA, Ramsar sites, Conservation zones, important areas for birds and bats	INEGI, 2014 CONABIO, 2014
5. Social conflicts with priority terrestrial zones	NO	Priority terrestrial zones	INEGI, 2014
6. Interference with water bodies and flows	NO	Hydrological regions, water bodies and flows	INEGI, 2014
7. Closeness to urban zones	YES	Inhabitants per municipality	INEGI, 2014
8. Existence of wind power projects	NO	Location of wind farms	SEGOB, 2013

NPA: natural protected area; Ramsar site: designated wetland of international importance under the Ramsar Convention.

Table II. Proposal of the 28 variables for the study, classified in four groups.

Variable	General description of the project's variables	Group
1. Construction	Constructing additional roads and infrastructure for the project	Technical
2. Viability	Estimating under minimal technical conditions the technical viability of the project	
3. Location	Identifying the availability of the best location for a wind farm	
4. Useful life	Calculating under ideal conditions the useful life span of the project	
5. Execution	Time of execution for the preparation and construction stages of the wind farm	
6. Information	Searching related literature and informing people about the application of the project	
7. Wind turbines	Analyzing the amount and type of wind turbines to be used in the wind farm	
1. Impacts	Identifying the initial economic impacts on the region generated by the project	Economic
2. Design	Proposing a profitable design for the wind farm according to the site	
3. Costs	Considering the basic investment costs for the wind farm	
4. Energy	Estimating the amount of energy generated by the wind farm	
5. Employments	calculating the number of new employments generated during the different stages of the project	
6. Recovery	Calculating the maximal period for the recovery of the investment	
7. Permits	Deducing the costs required for permits, paperwork, and facilities by local legal and authorities of the site	

Table II. Proposal of the 28 variables for the study, classified in four groups. (continued)

Variable	General description of the project's variables	Group
1. Buffering	Delimiting the buffering environmental area considering the main flora and fauna species of the region	Environmental
2. Noise	Identifying the levels of measurable noise	
3. Wind	Quantifying the amount and direction of wind in the area	
4. Limits	Considering the limits and locations of to protected natural areas and conservation areas	
5. Biodiversity	Estimating the diminishing or disappearance of animal diversity	
6. Vegetal	Estimating the diminishing or disappearance of the vegetal cover	
7. Soil	Physical and chemical modifications of soil caused by removal and activities in the used land	
1. Land	Management activities for the acquisition of the land required for the project	Social
2. Closeness	Considering the closeness of the wind farm to people affected by it	
3. Groups	Identifying and contacting social and cultural groups, as well as local leaders in the project's region	
4. Landscape	Considering changes in the regional landscape caused by the project and informing the community about them	
5. Accidents	Presupposing accidents that could occur to people and native fauna during the different stages of the project	
6. Conflicts	Managing conflicts of interest between the community and authorities due to the use of the selected land lots	
7. Insecurity	Considering the insecurity of the land and the presence of organized crime in the region of the project	

and society of a specific region. In addition, depending on its relevance each proposed variable was assigned a relative weight, which was obtained through consulting papers on planning and constructing wind farms with multicriteria considerations and the use of optimization methods (Moragues and Rapallini, 2004; Álvarez, 2006; Castillo, 2011; Caballero and García, 2012; ERM, 2014; Artillo, 2017; Obando, 2017).

2.3 Analytic hierarchy process (AHP)

The AHP proposed by Saaty (1977) is a multicriteria decision-making technique that simplifies a problem and assesses the relative relevance of criteria and alternatives. The main benefit of using AHP consists

in converting objective and subjective judgments into relative weights according to the relevance of the variables. This structured method optimizes complex decision making when there are multiple criteria or attributes, by means of breaking up the problem into a hierarchical structure, easing the handling of the problem by dividing it into a set of individual problems. We used this technique because it allows to understand the problem since it can be analyzed independently, leading to a solution that involves a large number of combinations and alternatives with the help of objective and subjective judgements.

There are many tools based on AHP, being one of the most used an open code software called Priority Estimation Tool (PriEsT). It is an interactive tool to

support the analysis of decision making aimed at estimating priorities based on pairwise comparison judgments. It helps decision makers to estimate their preferences for classifying options and adopt judgments for each criterion and reach a final classification. It offers a wide range of optimal solutions based on multi-objective optimization, in contrast to other techniques that offer only one solution (Siraj et al., 2015).

In the used methodology, 28 variables were considered that were assigned weighting values, depending on their relevance (Table III). The assignment of each variable in this study was based on an extensive review of literature on eolic projects.

Table III. Assignment scale of the pairwise comparative relevance (Saaty and Vargas, 1991).

Weighting values	Score
Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equally important	1

The AHP was applied to each group of variables with the PriEst software, which analyzed the matrix hierarchical patterns by making a pairwise comparison of the constituents in each level with their priorities, calculating the contribution of each alternative. From each analyzed group, the two variables with the highest weighting were chosen, considering them as the most relevant for the project. Then a similar procedure was performed with PriEsT to the eight resulting variables in order to prioritize them and their incorporation into GIS, which allowed their utilization in information layers.

2.4 Geographical Information System (GIS)

Once the eight most important variables were obtained from the AHP, they were transformed from their numerical values into spatial (maps of variables) and then vector maps, aimed at obtaining raster-type maps for each variable (a requisite for applying map algebra). Optimization values were assigned (Table III) to each grid of the study area for each raster map,

and a scale of three colors was determined according to the obtained numerical values, namely: optimal (green = 9), mid-optimal (yellow = 5), and not optimal (red = 1). With this classification, eight maps were obtained with vector information, to which a weighted overlapping process of layers in the GIS was performed. The weighted overlapping allowed for multicriteria evaluations to resolve the decision-making problem in which numerous factors with different assessments participate (Castellanos, 2017).

3. Results

Table I shows that the states of Baja California Norte, Sonora, and Tamaulipas are excluded as they do not comply with criterion 3. In this way, the analyzed area considered information on the sites in Chihuahua, Coahuila, Durango, and Nuevo León. Figure 2 shows the area that complies with the set of established criteria (area of active cells).

The proposed area encompasses an extension of approximately 34 900 km² with maximal distances of 310 × 160 km. The whole area is divided in grids of 100 km², which is a mid-detail and regional measure. It includes important municipalities like Torreón, Matamoros, Viesca, Parras, San Pedro, General Cepeda, Carmen, Ramos Arizpe, Saltillo, García, Mina, Hidalgo, Abasolo, and General Escobedo.

3.1 Analytic hierarchy process applied to variables

Table IV presents the results of the priorities estimation analysis using PriEsT. In this way, it was possible to choose the two highest values of each group obtained from the eight most relevant variables for the project. As a result of the process, the most fundamental variables for the study were:

- Technical: construction details and viability of the wind farm.
- Economic: estimated cost and investment recovery time.
- Environmental: amount of wind and animal biodiversity.
- Social: acceptance of the project by social groups, and level of insecurity in the area.

Table V shows the analysis made to estimate the most relevant priorities using PriEsT for the eight variables. Results point out that variables with the highest

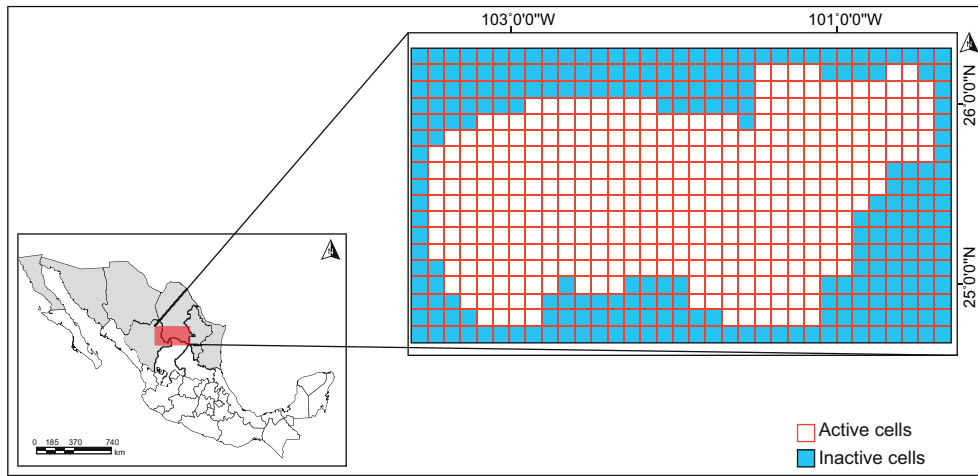


Fig. 2. Location and limits of the study area.

Table IV. Results of the PriEsT software for the 28 variables and their specific weight.

	Variable	Calculated specific weight
Analytic hierarchy process applied to the technical group	V1. Construction	0.279
	V2. Viability	0.268
	V3. Location	0.169
	V4. Useful lifespan	0.033
	V5. Execution	0.14
	V6. Information	0.061
	V7. Wind turbines	0.050
Analytic hierarchy process applied to the economic group	V8. Impacts	0.065
	V9. Design	0.116
	V10. Costs	0.254
	V11. Energy	0.206
	V12. Employments	0.062
	V13. Recovery	0.237
	V14. Permits	0.06
Analytic hierarchy process applied to the environmental group	V15. Buffering	0.063
	V16. Noise	0.064
	V17. Wind	0.231
	V18. Limits	0.084
	V19. Biodiversity	0.364
	V20. Vegetal	0.114
Analytic hierarchy process applied to the social group	V21. Soil	0.08
	V22. Land lots	0.079
	V23. Closeness	0.086
	V24. Groups	0.183
	V25. Landscape	0.036
	V26. Accidents	0.035
	V27. Conflicts	0.176
	V28. Insecurity	0.407

Table V. Summary of the eight best variables analyzed with the PriEsT software.

Type	Variable	Calculated specific weight	Information used for vector maps
Technical	Construction	0.132	Highways and roads (INEGI, 2014)
	Viability	0.079	Soil use (INEGI, 2014)
Economic	Costs	0.121	Population (INEGI, 2014)
	Recovery	0.139	Infrastructure (INEGI, 2014)
Environmental	Winds	0.152	WRF model (WRF, 2016)
	Biodiversity	0.132	Biodiversity (CONABIO, 2014)
Social	Groups	0.085	Social backwardness (CONEVAL, 2010)
	Insecurity	0.160	Robberies and homicides (INEGI, 2014)

weight for the project are: insecurity and winds, which correspond to the social and environmental groups, respectively. The recovery variable appears as a third relevant option for the project, although with a similar relevance as biodiversity and construction.

3.2 Feasibility map for wind farms

Firstly, with the vector information in Table V and the distribution of active cells in Figure 2, we calculated the initial optimal maps of variables in Table V. Thereafter, the specific weight value of each cell in these maps was assigned, in order to transform them into raster-type maps.

The eight raster-type maps grouped in pairs and types of variables (technical, economic, environmental, and social) were subjected to a map algebra process, obtaining four maps for each of the proposed types.

The wind farms feasibility map is the result of another map algebra process, which used the previous four maps. Algebra map allows the generation of a feasibility map in a colored chart (Fig. 3), which served to identify the most adequate areas to develop a wind farm. The percentage of feasibility varies according to the colors in the chart of optimal sites.

Figure 3 shows the north and northwest regions with the best feasibility for the development of wind farms. Light-green cells indicate a 70 to 80% feasibility, and the yellow cells correspond to a 60 to 69% feasibility. This map favors environmental features, with a good amount of wind and low impact on the fauna. Regarding the social aspects, it does not present organized social groups and corresponds to a secure zone. These two subsections received weights slightly higher than the technical and economic variables.

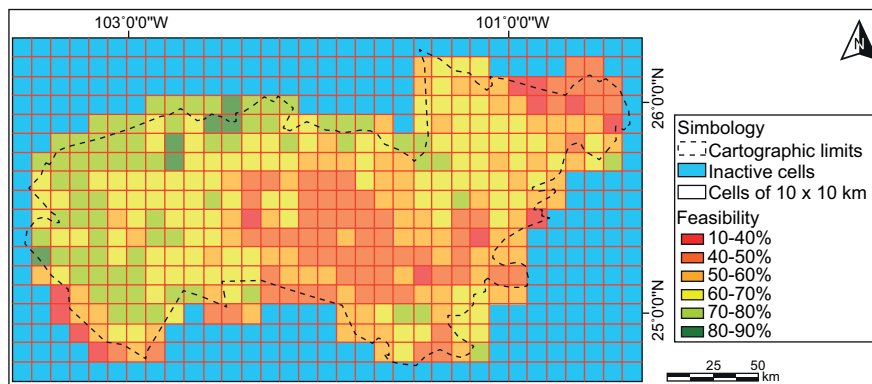


Fig. 3. Map of optimal sites with feasibility values associated with a table of values to install a wind farm.

Regarding the worst sites, they are located in the central and northeast regions, where feasibility is below 50%. According to our data, these regions have social perturbations like robbery and criminality and the required amount of wind is minimal, so they would pose technical risks for the project.

Finally, there are six dark-green cells in the north-west region which comply with the best feasibility conditions (80-90%). At the municipal level (INEGI, 2015), they would correspond to the southwest of Coahuila, specifically to the municipalities of San Pedro (106 142 inhabitants), Matamoros (108 950 inhabitants), Torreón (679 288 inhabitants), and Viesca (21 549 inhabitants). Thus, these are considered the most adequate zones for the development of a wind farm.

4. Discussion

The north of Mexico has a considerable number regions adequate for the development of wind farms, as can be observed from the followed methodology using only digital cartographic information (Table I). This technique is useful to roughly locate sites for exploitation. In addition, if meteorological information from the WRF is implemented, allowing for a lengthier temporal measurement of the wind factor (5 years), the uncertainty for estimating possible sites is reduced. This contrasts with yearly measurements to obtain information on the wind factor, which in some cases are only intermittent and scarcely reliable (ERM, 2014).

The southern part of the state of Coahuila presents the best options for wind farms, as it has industrial infrastructure and a territory with few environmental conflicts (in relation to the limits of natural protected zones). These conditions strengthen the possibility to support this type of projects.

The use of hierarchical algorithm was proposed to ease and optimize the decision-making process when gathering results that contemplate the largest number of criteria and conditions, in order to obtain the best alternatives for this complex project. The posed criteria were divided in four groups covering the most important aspects in the technical, economic, environmental, and social areas (Table II). Based on the literature and prior contributions to this type of projects, representative values were assigned to the variables (Table IV).

In most eolic projects, technical and economic criteria are considered as the most relevant. However, in this study, environmental and social variables were given a greater importance, fundamentally with the idea of causing minimal disturbance to the flora and fauna of the region and providing benefits to the local populations by generating employments, activating the economy, and diminishing the consumption of traditional energy.

The use of a hierarchical process in this study allowed obtaining results that incorporate a large number of criteria for the decision makers, by organizing efficiently and graphically the information regarding the decision-making process. The construction of maps of variables eases the handling and interpretation of data (Xu et al., 2012).

The proposed methodology allows resolving problems that include multidisciplinary aspects, and offers the involved groups a solution that can be easily understood and accepted (Janke, 2010, Kang et al., 2011; Díaz et al., 2017), in contrast with some studies on the feasibility of sites for wind farms where only techno-economic aspects (knowing where to place the wind turbines, calculating economic losses, increasing the efficiency of the wind farm, etc.) are taken into account (EWEA, 2009).

5. Conclusions

The process of choosing a location for installing and developing wind farms is a complex task due to compulsory regulations and requirements; hence, this type of study is a good option for Mexico.

The use of multicriteria computational hierarchical algorithms eases the task of decision makers to select the location of a wind farm. The advantage of this methodology is its great usefulness when decision elements are scarcely known and difficult to quantify and assess, as it permits calculating the contribution of each alternative with respect to the others. This methodology can be applied in other regions of the country, as long as the variables of interest are well defined and evaluated.

The AHP, using the PriEsT software, is a useful tool for selecting the most relevant variables for the project. AHP allows estimating priorities based on pairwise comparison judgments. It offers a wide range of optimal solutions based on multi-objective optimization.

The use of GIS to couple the analysis of the best variables yields visual results of the feasible sites.

The resulting optimal sites map reveals numerous sites with values from 10 to 40% and 80 to 90% for the least and most feasible locations, respectively.

The western region of Coahuila presents the best areas with adequate features according to the set of chosen variables. In particular, the municipality of San Pedro, has a surface of 300 km² for the installation of a wind farm with a feasibility of 70 to 80%.

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