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Multi-criteria decision support system for wind farm site selection and sensitivity analysis: Case study of Alborz Province, Iran

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ABSTRACT

Renewable energy resource assessment critical input to national development planning. This paper analyses a multi-criteria decision support system to estimate wind energy resources in central Iran. The Multi-Criteria Decision Making (MCDM) method and site selection criterion for wind resource assessment using ArcGIS are described and developed for the study area. Structural, topographical, and ecological criteria, along with their sub-criteria, have been directed to eliminate unsuitable locations. The methodology takes into account the slope of the terrain, wind speed, distance from the electricity grid, distance from substations, distance from urban areas, and distance from highway and roads as AHP (Analytical Hierarchy Process) criteria. The results of the study show that 20% of the study area is suitable for wind farm development. The South East area of the province, including Karaj and Nazar Abad County, is the highest priority part of Alborz province. A sensitivity analysis indicates that results were generally reliable; however, eliminating the electrical criteria is the best way to enhance the area of available land for wind farm development.

1. Introduction

In recent decades, providing sustainable and available sources of energy for human communities is one of the biggest challenges. World energy demand is expected to gain an average of 8% increase per year between 2000 and 2030 [1]. Fossil fuels provide a large portion of the energy needed, which has the most powerful effects. Several developed and developing countries have adopted policies towards the use of renewable energies such as wind and solar power to reduce their dependency on fossil fuels.

Wind power is one of the most reliable and secure form of renewable energy. Wind currently stands as a steadily growing, environmentally friendly, and economically viable resource. It has turned out to be further appealing as a clean, renewable energy resource due to the growth and reduction of energy conversion technology. The significance of wind power has risen in recent years due to employing a diverse encouraging policies in states for establishing wind farm power plants. The price of power production from wind energy has become competitive with that of power from fusil fuels. Therefore, wind power is an accepted and harmless type of renewable energy that can be cost-effectively viable, environmentally safe, and can play a significant role in reduction of CO_2, SO_x, and NO_x [2].

Wind energy is appealing for policymakers because of its low environmental and energy costs; meanwhile, it reduces dependency on fossil fuels and helps in economic growth. Therefore, wind energy is a factor in satisfying the current goals set by the national policy in Iran. Since wind power is a clean and renewable energy resource, on the issue of worldwide concerns about climate change and energy sources, it has enjoyed highly-flavored and steady levels of public verification. Accordingly, developing a methodological process of wind farm site selection is the primary purpose of this research in order to obtain energy diversity.

The purpose of this study is the need for new energy resources due to population growth. Iran's domestic consumption and production have been grown progressively since 1984 and are still strongly dependent on traditional thermal energy sources of electricity, with a small fraction produced by hydropower plants. Iran's electricity consumption will increase in the following decades to about 6% per year.

Categorizing suitable regions with sufficient wind resources and additional standards is a complicated task. Location-based decision-making by a combination of the outcomes of studies and surveys is a process exposed to human error. In this study Geographical information

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systems (GIS) used as digital location-based calculation tool to minimalize errors by recognizing potential areas using digital thematic maps and conceptual models for data integration.

In recent studies, GIS is applied as a decision support system (DSS) for wind farm site selection. Ayodele and Ogunjuyigbe, in 2018 in Northern Nigeria, exercised an analytical framework using geographic information systems (GIS). This paper proposed a geographic information system-based model for wind farm site selection using an interval type-2 fuzzy analytic hierarchy process and implemented to determine the suitable wind farm sites in Nigeria. The model focuses on the use of fuzzy sets to represent the expert's linguistic judgment to address the issues of uncertainty and inconsistency in wind farm site selection. The model uses two sets of criteria (weighted and constraint) which are either economic, social, or environmental to evaluate the suitable sites for wind farm development [3].

Pambudi and Nananukul, in 2019, applied a hierarchical binary data envelopment analysis (DDEA) model to identify a suitable location for building a wind farm. The analysis considered the essential factors related to geographical and structural data. The DDEA method is a multi-criterion and non-parametric estimation method to measure DMU performances. The proposed hierarchy consists of two levels, which are defined based on 165 districts and 33 provinces in Indonesia [4].

Messaoudi and et al. (2019) applied a methodology that is mainly composed of two stages: the first stage is to evaluate and select the best locations for wind-powered hydrogen production using GIS and MCDM technique. The second stage is applying different filtration constraints to select the suitable petrol stations for such hydrogen refueling station modification [5].

The multiple criteria decision-making method and site selection criterion for wind resources assessment were explained and developed by Noorollahi et al. (2016) [6]. Criteria of equal importance were investigated, including technical, environmental, economic, and geographic standards. The outcomes were satisfactory for electricity production under international standards from wind in western Iran.

Hofer and et al. (2016) in Städteregion Aachen Germany applied a GIS-based Analytic Hierarchy Process approach. A group of local experts and stakeholders filled out the pairwise comparison of the incorporated criteria [7].

Haaren and Fthenakis have conducted a study in the State of New York, U.S., and applied more different ecological and economic criteria to the Janke's factors, such as the avoidance of avian impacts and economic costs to the wind power [8].

Concerning other decision support systems for wind energy projects such as Cost-Benefit Analysis, Diakoulaki and et al. (2007) performed the parallel application of two progressively used decision support techniques, multicriteria decision analysis, and cost-benefit analysis [9].

For a better understanding of the methods applied in previous studies and a comprehensive comparison of the ANP and AHP procedure, Ilbahar and his colleagues outlined a research in Ref. [10].

Some other studies consider the regional sustainability of renewable developments. Smetana and et al. (2015) studied the best methods for sustainability assessment and identified the necessities of regional systems. Further, they proposed the concept of regional sustainability assessment methodology (RSAM) [11]. Head and et al. (2011) presented that governments have several types of complications in planning and employing policies for sustainable regions. They demonstrated that the difficulties arise from crucial factors: One is the complexity of regional sustainability issues. Another type of difficulty arises from the institutional features of the public sector itself [12].

The most important innovation of this study is the consideration of electrical criteria to determine the potential sites for wind energy resources in Alborz province, Iran. Criteria reviewed by considering geological, electrical (power loss, which results from long distance from the electrical power lines and electrical limitations of the power stations), and economic standards and alienated into two parts, covering restrictive and categorizing layers. The consequences were encouraging for electricity generation in harmony with global standards from wind farm site selection in central Iran.

Following the paper includes: Section 2 introduces the study area. Section 3 explains the AHP processes. Section 4 describes the AHP weights and supports the criteria explanation, and section 5 describes the methodology for the study. Section 6 presents the results of the analysis. Section 7 provides a sensitivity analysis of the AHP criteria, and Section 8, represents conclusions.

2. Study area

Alborz Province is one of the 31 provinces of Iran, centered in Karaj. Alborz Province was established by the division of Tehran Province into two provinces, after the Parliamentary approval on June 23, 2010 [13]. Situated northwest of Tehran, the Province of Alborz has four counties, Karaj, Savojbolagh, Taleghan, and Nazarabad (see Fig. 3). Karaj is the center of the province. Alborz Province is situated 35 km west of Tehran with a total area of 5,833 km^2, at the hills of the Alborz Mountains, and is Iran's smallest province in the area. According to the National Census, in 2011, the population of Alborz was 2,412,513, out of which 90.5% lived in urban areas [14].

In recent years, the development and formation of essential factories and extensive manufacturing facilities for chemicals, textile, non-metallic minerals, metal, petrochemicals, pharmaceutical, and food industries have been used in the quick expansion of the Karaj county region. The growth of industrial sectors and high population growth in this county necessitate the expansion of green energy resources. The industrial sector has enlarged all types of ecological contaminations, thus developing new energy sources such as wind energy with low environmental impact is critical.

Iran electric power market has progressed over the past 43 years. Its domestic consumption and production have been grown increasingly since 1984 and are still profoundly dependent on traditional thermal sources of electricity, with a small fraction being produced by hydropower plants. Electricity consumption of Iran is expected to grow at about 6% per year in the following decades. Fig. 1 shows electricity production and consumption growth in Iran during the past decades [6].

Alborz province consumes about 2.013% (5,817,667 MWh), of total electricity production in Iran for its 2,412,513 million people and 1,247,024 power consumers in six categories. The first category is household users (2,080,787 MWh), covering 35.77% of consumption. Commercial consumers (557,316 MWh) use 9.58% of electricity. Industrial consumers (1,740,105 MWh) use 29.91% of the power. Public consumers (603,772 MWh) consume 10.38% of electricity. The agricultural sector (705,722 MWh) consumes 12.13% of electricity [25]. The remaining users consume only 129,965 MWh of electricity, which is

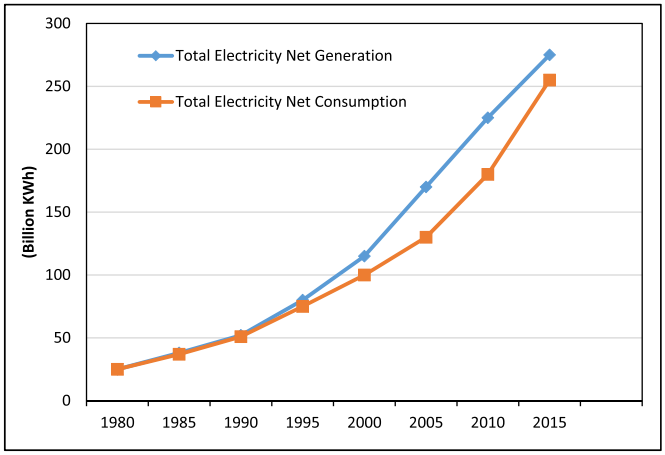


Fig. 1. Electricity production and consumption growth in Iran [6].

only 2.23%. Fig. 2 shows the usage of electricity by different consumer categories in Alborz province [15,16].

The management sector for Alborz electricity production and distribution must concentrate their endeavors on meeting this continuing growth in demand. Currently, Alborz produces 2% of total electricity but consumes 2.013%. There is no power plant under construction, even though consumption is growing by 4.5% annually [15,16]. The development of renewable energy resources such as wind energy can help to meet this increasing energy demand.

3. Analytical Hierarchy Process

Wind farm site selection is an intricate decision-making problem, including multiple criteria and alternatives. MCDM procedure prepares an intellectual framework to survey, analyze, and solve such problems [17,18]. AHP (Analytical Hierarchy Process) is one of the most thorough methods which has been considered for multi-criteria decision making. The scheme was employed for the first time in 1980 by Saaty [19]. This technique provides a formulation of the problem for the hierarchical along with competence of taking into account qualitative and quantitative criteria in interpreting problems [20]. This method has diverse selections in decision making, comprising sensitivity analysis on the criteria and sub-criteria. Furthermore, AHP is based on the pair-wise comparison, which facilitates judgment and computations. Additionally, AHP points out the compatibility and incompatibility of decision which is one of the exceptional advantages of this procedure on multi-criteria decision making.

The experts who participated in the questionnaire are human beings, and humans are faulty at making rational decisions that draw on multiple dimensions. In 2 or 3-dimensional decision-making processes, biases will influence the decision without the decision-maker even being aware of it and AHP helps address this issue. It constructs the judgment in a way that helps to reduce decision bias — The AHP unbiased conduction of decision making is the primary reason to choose that method for this study.

The purpose of constructing a hierarchy of decision trees is illustrating the four levels of decision makings, comprising goals, criteria, sub-criteria, and choices [21]. Converting issues or problems into a hierarchical form is an essential part of the Analytic Hierarchy Process [22].

The initial step of this technique is converting of the decision problem in a hierarchy. The AHP method demonstrates the ultimate goal of the decision-making process at the peak, criteria affecting the choice at the middle body, and choices at the bottom. The AHP exerts a substantial nine points measure to display singular superiority [19]. The essential nine points utilized for these pairwise evaluations are in Tables 1 and 2.

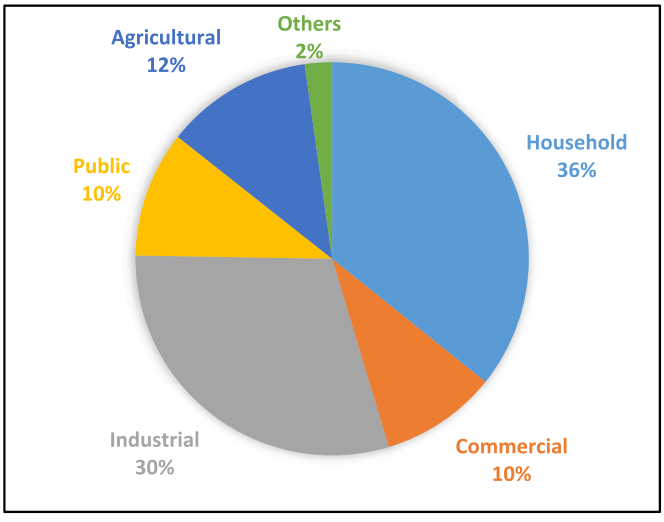


Fig. 2. The share of electricity in different sectors in Alborz province [15].

These averages exclude relative weights (w) of the comparison criteria. One of the AHP advantages is providing the possibility of defining the compatibility of judgments for each criterion. The arranged mechanism that planned to assess the adaptability of judgments is computing the Consistency Ratio. The consistency ratio (CR) expresses how coherent the decision-maker is with his responses. As a whole, a quantity of 0.10 or higher recommends that the decision-maker is supposed to reconsider the answers in the course of pairwise comparison. In a consensual matrix, the principal eigenvalue (λ_{max}) is always higher than or corresponding to the number of rows or columns (n) if a pairwise comparison does not comprise any incompatibility, $\lambda_{max} = n$.

A consistency index (CI) that shows the incompatibility of pairwise comparisons can be assessed as following [19]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

Moreover, a measure of the pairwise evaluations can be calculated by the following equation in term of consistency ratio (CR):

$$CR = \frac{CI}{RI} \quad (2)$$

The random index values (RI) are offered in Table 2. RI is utilized to calculate CR, which varies with the matrix size. As a principle, a CR value of 10% or less is accepted. Otherwise, decision-makers have to review their decisions [24].

4. AHP weights

AHP criteria containing wind speed, distance from power lines, distance from substations, distance from highway and roads and urban areas, and also the slope of terrain are considered based on expert suggestions and previous studies. The hierarchy diagram of criteria was suggested in Fig. 4.

The criteria compared in pair-comparison matrices with each other, and the weight of each criterion in terms of its priority is assigned. Scoring has been applied based on expert opinion through a questionnaire.

Experts are mainly university professors and researchers in the field of renewable energy. Appendix A (Table 10) shows the individual experts, organizations, and their field of expertise. The questionnaires have been sent to them via email or submitted to them in person. The survey process has been conducted by putting the weights, taken from questionnaires, into Expert Choice software to calculate the final rates of each criterion.

During pairwise comparison for each set of criteria, inconsistent rate analysis was implemented.

According to our final questionnaires, the preference vectors are accounted for using the eigenvalue method. The personal priority of the experts is accumulated in order to deduce the comparative significance of the weighted criteria. The accumulation is done with the geometric mean method in the following equation [26].

$$p_f(c_j) = \prod_{i=1}^{n} p_i(c_j)^{w_i} \quad (3)$$

In which, and w_i is the weight of each individual that in our research we used the same weights for each person, $p_f(c_j)$ is the final weight of criterion j, $p_i(c_j)$ refers to the weight of criterion j by individual i. The final ranking of AHP criteria is summed up in Table 3. The CR value for each of our comparison matrixes was lower than 10%, which implies that the pairwise matrixes given by the consultants are not required to be revised.

Considering criteria weights based on the AHP model and providing data sheets, the GIS software was used to overlay the maps, and

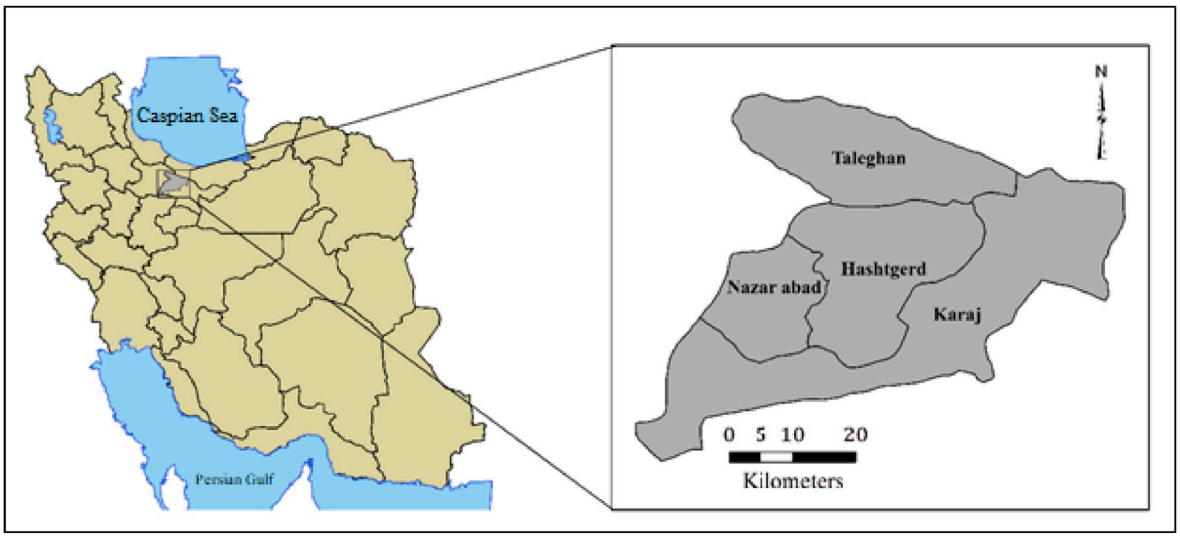


Fig. 3. Location of Alborz province in Iran.

Table 1
The nine points scale, according to Saaty [19]. The following footsteps are as below [23].
a) Sum the values in each column of the pairwise comparison matrix;
b) Divide each point in the matrix by its column's summation (normalizing);
c) Calculate the average of the quantities in each row of the normalized matrix.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Extreme importance	An activity is favored very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed

ultimately the locations for constructing wind farms were created. Fig. 5 displays the methodology of the study. Restricting factors along with the minimum and maximum distance from each criterion have been determined by taking into account the electrical, environmental, technical, and economic principles based on expert opinion and national and international standards and in accordance with the national legislation of the country.

5. Methodological framework

Supervising information and data in an appraisal scheme necessitate uniting and clarifying the consequences to distinguish the sites and fields of the region proposed for a precise investigation and establish positions for potential wind farms. A great deal of technical and non-technical tools are needed to identify apposite sites [6]. This is a daunting effort for a project instructor and executives. Thus, the process is segregated into two steps.

Based on the methodology of the study, in the first stage, the study area was divided into two segments. In the second step, the possible sites were organized by overlaying representative layers using ArcGIS for each criterion and their related weights corresponding to the importance of the criterion. In the last stage, the final wind farms have been planned.

5.1. Restrictive process

The restrictive procedure enjoys three sub-layers, structural, topographical, and ecological study. In the previous Iranian studies [2,6, 27–29], setting data layers and their standards were inspected and fixed for Iran, employing constitutional and local regulations and rules. The restrictive criteria buffer zones for potential wind farms are given in Table 4. The restrictive method uses the Boolean logic approach to define the possibility of locating a wind farm based on a predefined criterion. Boolean logic applies a binary condition to inputs and evaluates a binary condition for the output. Logical math tools represent false conditions as 0 and the right conditions as any value other than 0. In this method, based on every criterion, the study area is classified into two discrete classes; 1 for the area with a probability of being a wind farm location and 0 for an area with an impediment for wind farm locating. The main steps in the restrictive method are:

- Development of a conceptual model.
- Defining specific criteria for site selection.
- Collection of data and information.
- Assessment and characterization of the study area.
- Identifying promising areas based on criteria defined for every data layer.
- Developing a data integration method based on the conceptual model.
- Defining the most promising potential wind sites.

A conceptual model of the restrictive method is shown in Fig. 6. More than 15 data layers were used to analyze the study area into two (suitable or unsuitable) locations.

Table 2
Random index values based on Saaty and Tran [25].

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

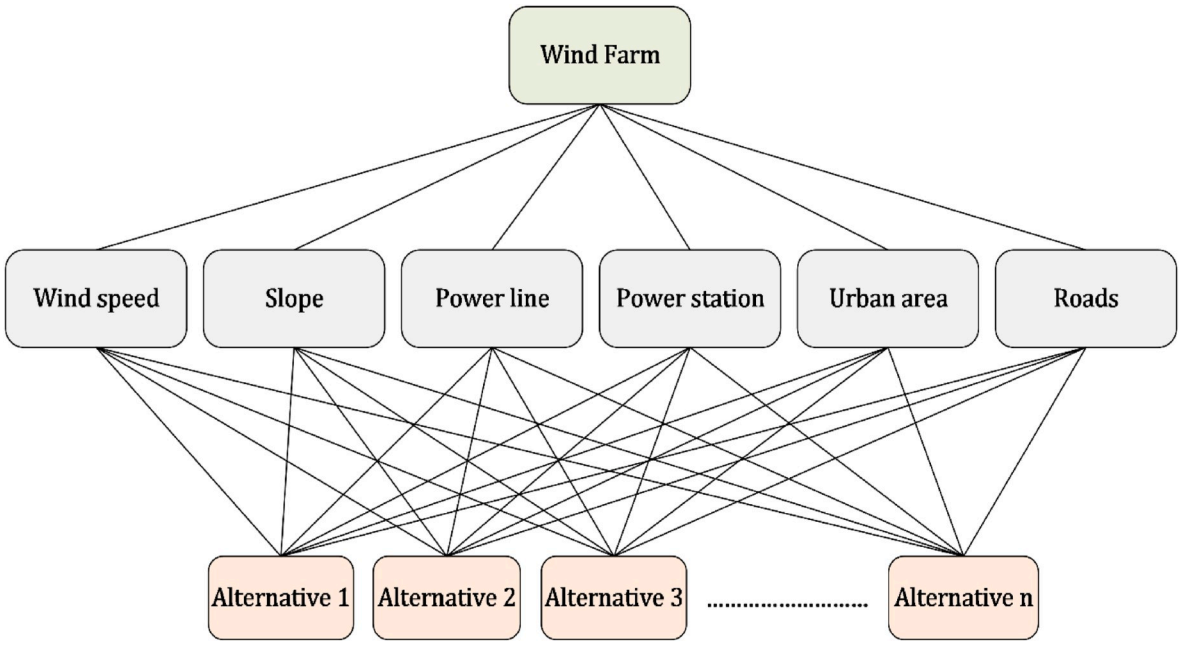


Fig. 4. Decision process hierarchy.

Table 3
The relative importance of AHP criteria and overall inconsistency.

Classified criteria	Weight [%]
Wind energy potential	38.9
Distance from power lines	27.7
Distance from highways and roads	14.4
Distance from substations	8.4
Distance from urban areas	6.8
Slope of terrain	3.9
Inconsistency ratio [%] = 4	

5.1.1. Structural unsuitable zones

Structural limitations applied based on criteria in Table 5. According to the Iranian Ministry of Energy protocols, constructing new structures closer than 250 m to power plants is prohibited [6]. Well-situated sites are those rather than 2500 m in the distance from airports and more than 300 m from railways [2,30]. Following the description above, unsuitable structural areas in Alborz province are exposed in Fig. 7.

5.1.2. Topographical unsuitable zones

For the appropriate topographical layers, the outline model applied a digital elevation model (DEM) to create the slope map of the province in percent; Terrain with slopes less than 30% were proposed non-zero for wind farms development, and the highest slope of 30% is assumed. Similarly, DEM was employed to specify applicable terrain based on elevation. Meanwhile, wind energy effectiveness diminishes as air density decreases at higher elevations, and 2000 m altitude was selected as the cut-off level. For faults, a barrier zone of more than 500 m is weighed [2,30–32]. Fig. 8 shows unsuitable topographical areas.

5.1.3. Ecological unsuitable zones

Locating wind turbines next to suburban areas is constrained so as to prohibit noise nuisance and visual interruption or blade shadow effects by wind turbines [7]. This criterion has been taken into account in many surveys [6,33–37]. Moreover, regions with less than 2500 m distance from municipal areas and with 500 m from countryside districts are restricted [6,30,38].

In 1967, the Department of the Environment (DOE) of Iran announced 15 protected areas, including national natural monuments, national parks, wildlife sanctuaries and protected areas in the country. By 2005, DOE declared that there are 160 zones with an annual ratio growth of 4.2%, covering 7.17% of the total country area (11,842,599 ha). Based on DOE rules, a 2000 m buffer zone from protected areas is compulsory for any development. The prohibited span from ancient and cultural monuments is 700 m [39]. The excluded buffer zone around rivers, lakes, and water bodies are 500 m and 700 m, respectively [2,6,31]. Inappropriate sites based on the ecological criterion and final unsuitable areas are presented in Fig. 9 and Fig. 10, respectively.

5.2. Categorizing method

In this stage, data layers containing detailed wind speed map, the slope of the terrain, distance to the electric power lines, distance from substations, distance from urban areas, and distance to highways and roads were utilized to settle suitable sites and establish particular classes for wind farms. AHP weight factors were assigned to each subclass, and the region was organized into several subclasses for every data layer corresponding to its importance related to other subclasses.

5.2.1. Wind energy potential

The wind energy potential criterion is the most critical principle in almost all the studies [33–35,38]. The average wind speed in the region is a core criterion with respect to the economic proficiency of wind farms [7]. Winds are intensely influenced and reformed by plants cover, water bodies, land use patterns, local terrain, weather conditions, and numerous additional features. More than 130 wind synoptic stations were installed across the country to prepare a wind atlas for Iran. These stations record wind data every 10 min, and the effects of tempest and chaos on the wind stream are taken into consideration in the outcomes. The information delivered in this study is based exclusively on Iran wind data and indicates the attributes of Iranian wind resources.

The computations were based on numerical flow simulations using the 3D atmospheric model KLIMM, which is mainly intended to account for the multipart configuration of the terrain (topographic elevation and land use distribution). The KLIMM model flowchart is shown in Fig. 11. KLIMM is a 3D numerical mesoscale model of the atmosphere that reproduces wind conditions at many spots in the atmosphere. From this and analysis of regular meteorological stations and locally evaluated wind source data, the long-term annual wind speed for any location can

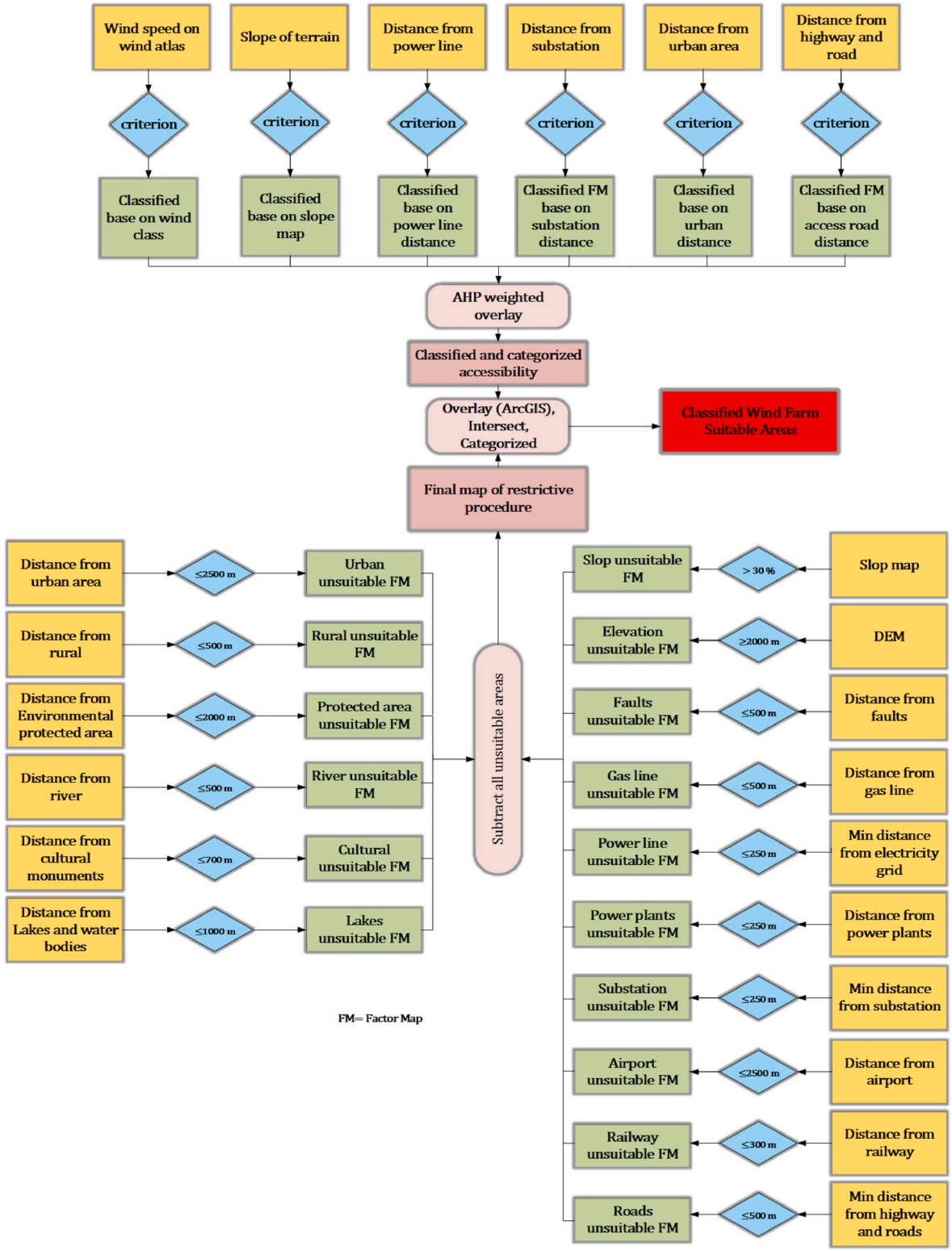


Fig. 5. The methodology of the study.

be determined [41].

A digital numerical model to explore the region was formed using topographic elevation and land use data for the net dimension of 200 m in resolution. For confirmation and sufficient modification of the evaluated outcomes, statistics from 130 wind measuring stations for an interval of at least 24 months were used (10–40 m above ground). Computational flow calculations were implemented for distinguishing meteorological sites (representative scenarios). All results of the individual scenarios were combined for representative annual average wind speed depending on the statistical frequency for each specific scenario. At the same time, as evaluating the outcomes (cross-validation), wind speeds were computed at representative locations. On the basis of the fine-adjustment of the three-dimensional wind fields, the spatial distribution of the annual wind speed was defined for all areas. The resulting

Table 4
Restrictive criteria buffer zones.

Criteria	Sub-criteria	Logic Input	Buffer zones	References
Structural	Distance from the electricity grid	D_1	0–250 m	[2,6,40]
	Power plants	D_2	0–250 m	[2,6]
	Substations	D_3	0–250 m	[2]
	Gas transmission line	D_4	0–500 m	[2]
	Railway	D_5	0–300 m	[6]
	Highway and roads	D_6	0–500 m	[6]
	Airport	D_7	0–2500 m	[6]
Topographical	Elevation	D_8	>2000 m	[2,6]
	Slope	D_9	>30%	[7]
	Faults	D_{10}	0–500 m	[6]
Ecological	Environmental protected area	D_{11}	0–2000 m	[2,6]
	Ancient and cultural monuments	D_{12}	0–700 m	[6]
	Lakes and water bodies	D_{13}	0–1000 m	[6]
	River	D_{14}	0–500 m	[6]
	Distance from an urban area	D_{15}	0–2500 m	[38]
	Distance from the rural area	D_{16}	0–500 m	[6]

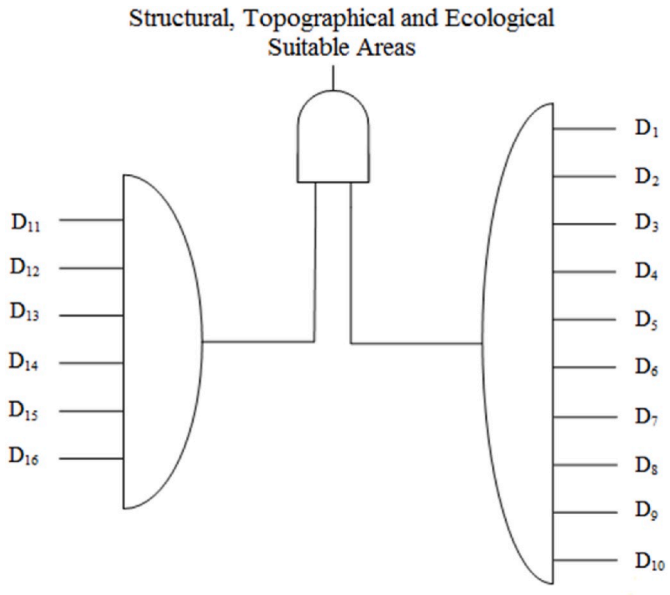


Fig. 6. A conceptual model of the restrictive method.

Table 5
The theoretical wind energy potential of Iran based on atmospheric analysis [42].

Item	Unit	>50 W/m^2	>100 W/m^2	>150 W/m^2
Coverage rate	%	80.9	38.9	9.6
Area (1,500,363 km^2)	Km^2	1,214,294	576,077	145,138
Energy potential	GW	725	450	152
Available energy potential	GW	–	–	143

wind map shows wind speed and wind power density at altitudes of 50 m and 80 m, which is the hub heights of modern wind turbines.

The wind potential points out several regions of suitable to very-suitable possible locations that are areas of interest for further wind farm expansion. Table 5 indicates the theoretical wind energy potential of the atmosphere corresponding to more than 50 W/m^2, 100 W/m^2, and 150 W/m^2 in Iran.

A comprehensive wind resource measurement using accurate position grounded statistics and tools such as GIS are compulsory. The current study described factors and criteria that are used for site selection and resource allocation. As shown in Fig. 12, the average wind speed map of Alborz province at 80 m for different speeds has been classified (Class 9 represents the most suitable area on the map). According to recent surveys [6] and our experts' opinions, wind speed below 5.6 m/s are no longer economically viable and are omitted.

5.2.2. *Slope of terrain*

The slope is a critical criterion for economic and transportation reasons. Some studies have not taken it into account [43–46]; however, some others paid more attention to the slope and have considered it as an AHP criterion [7,47]. In many studies, slope, more than 15%, is restricted [6,8,36]. In a mountainous and small area putting a strict slope, the restriction means to eliminate huge parts, limiting the installation of wind power significantly. Consequently, in our case, we enhanced our slope limitation to 30%. Slope limitation resembles the views of the local wind power specialists and wind farm developers who contributed to the inquiry. For this purpose, we benefitted the digital elevation model (DEM) to create the slope map of the region in percent. This study benefits from the latest release of the Advanced Spaceborne Thermal Emission Reflectometer DEM (ASTER GDEM2) based on the Shuttle Radar Topography Mission (SRTM) as released by the United States Geological Survey (SRTM3 USGS version 2.1). The study area was classified into eleven classes based on classification mentioned in Ref. [7]. Table 6 shows the area of each sub-class (in km^2) for the slope of terrain criterion. Fig. 13 shows the classified areas for the slope criterion.

5.2.3. *Distance from the electricity grid*

Studies that have previously been published have exclusively ignored their grid adjacency. [34,38,44]; however, the others considered it. Extensive evaluations have been carried out by Ramirez-Rosado et al. [48] and van Haaren and Fthenakis [8]. Proximity to the nearby grid is substantial for the feeder line, as well as a power loss (the shorter, the better). When suggesting a large super-megawatt wind farm coupling to the network, power flow analysis should be carried out in order to assess whether the downstream transmission lines are able to cope with the extra load or not [8]. Some extended analyses have to be implemented at the expense of the developer by the electrical experts. The proximity of only a high voltage line near to a compact or ordinary wind farm may not be profitable as the expenses of the connection to such a grid may be restrictive. Consequently, according to the Iranian protocols, buffer zones less than 250 m to the electricity grids are chosen as exclusive zones.

5.2.4. *Distance from substations*

Substations are essential for connecting a wind farm to the electricity grid. Interconnection assessments for a wind power plant can cost $5000-$150,000 or more, relating to the extent of the plan and location proposed to interconnect. Three-phase lines are needed for large generators, but they cannot carry the energy from wind turbines [49]. A 6 MW wind farm connecting to a 69 kV transportation line needs to construct a substation with costs in excess of $1 million dollars. The same 6 MW connected to a distribution system (usually less than 25 kV) without the need for establishing substation can cost one-fourth of this amount in interconnect fees [49]. Detailed typical charges for the installation of substations with different capacities are shown in Table 7. Therefore, it is more economical and technically reasonable to locate our wind farms close to distribution substations. On this basis, in our research, the value score decreases with increasing distance from substations.

5.2.5. *Distance from urban areas*

Establishing wind farms near urban and high consumption rate areas

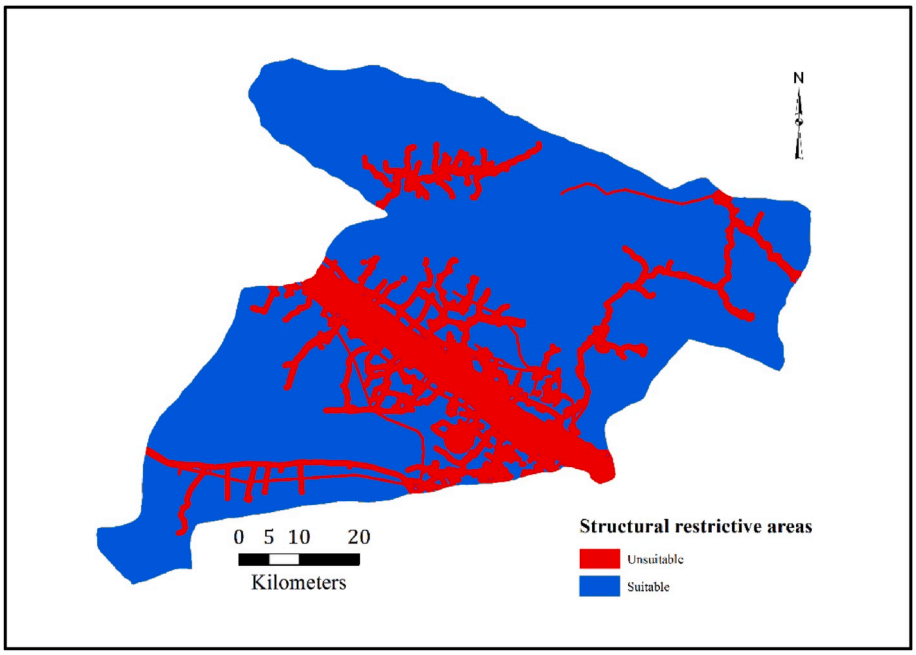


Fig. 7. Structural unsuitable areas.

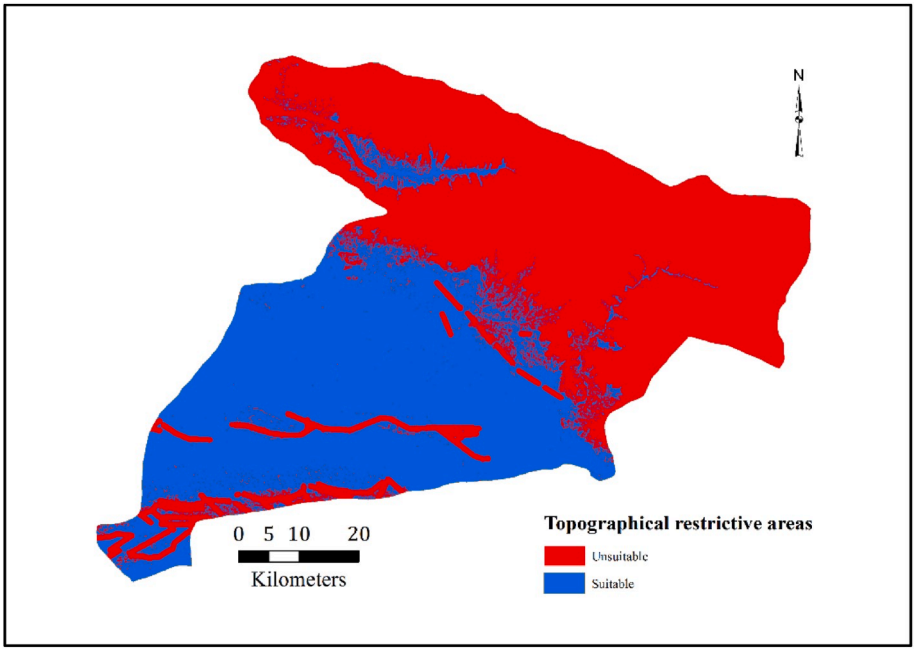


Fig. 8. Topographical unsuitable areas.

has economic benefits. Thus, locating wind farms near settlements with high electricity consumption, the energy generated from the farm will require fewer transmission lines to convey the power, so the cost of delivering the energy to customers would decrease. Therefore, the weight scores will diminish as the distance from urban areas increases, although a buffer zone of 2.5 km is considered for security and noise nuisance reasons [7].

5.2.6. Distance to highways and roads

The adjacency to main roads is indispensable because the transportation of massive turbines can be intricate and prohibitive [33]. The distance from the possible wind power plant to large roads or railways should be reduced to lower the costs. In almost all the studies, the areas closer to roads are more appropriate for establishing a wind farm [8,33,35,36,48,50,51]. According to Iranian Road Maintenance & Transportation Organization regulations (RMTO) and previous studies in the country, a minimum distance of 500 m should be kept from highways and roads [6]. Consequently, the nearer to transportation infrastructure, the higher the value (see Table 9).

Distance from highways and roads is shown in Fig. 14.

The final map of rated areas overlaid using the AHP method. In this method, data layers created for classified wind speed map, the slope of the terrain, distance from power lines, distance from substations, distance from urban areas, and distance to highways and roads were used

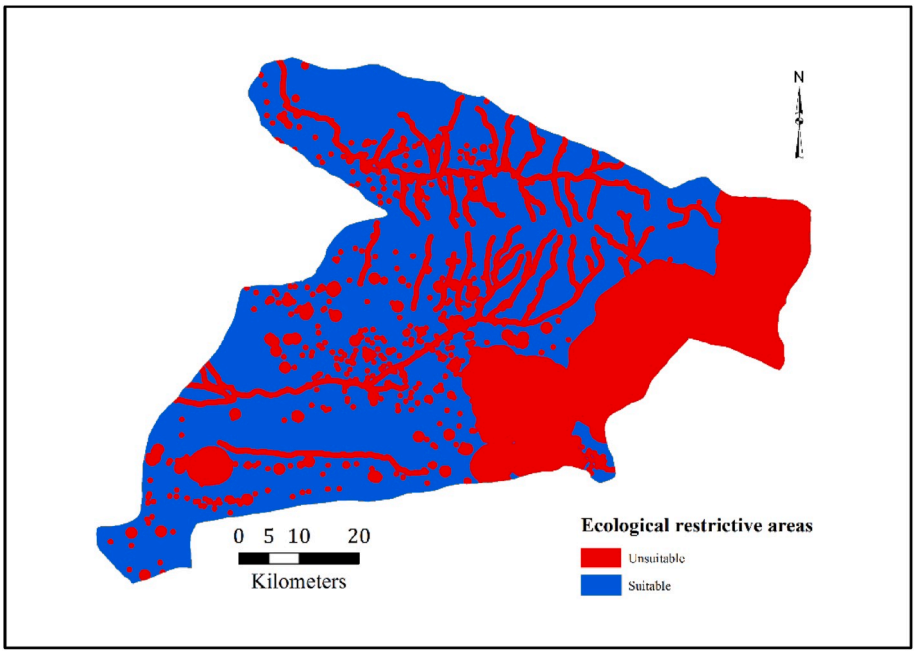


Fig. 9. Ecological unsuitable areas.

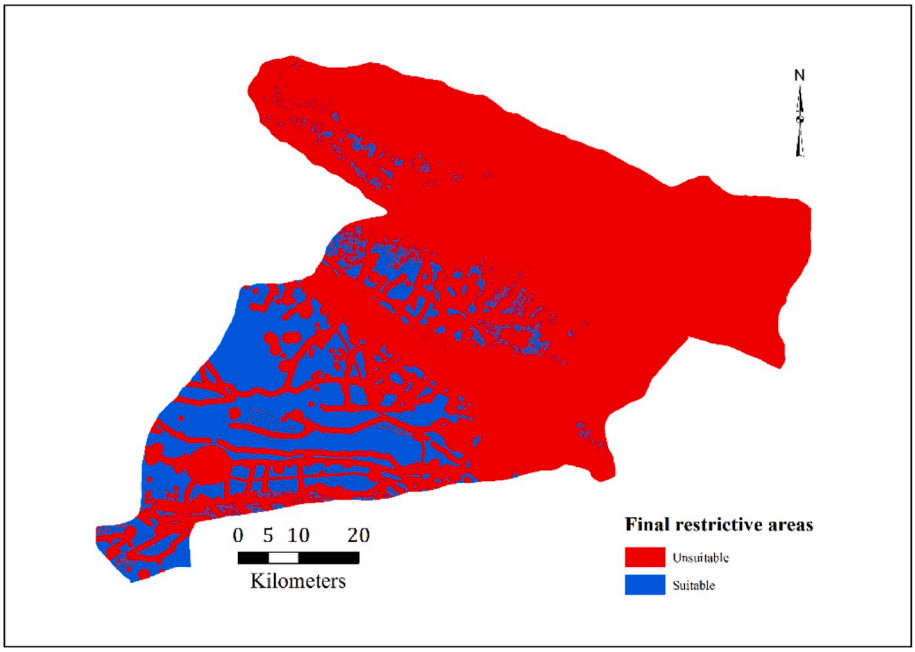


Fig. 10. Final restrictive areas.

to locate appropriate sites and classify particular locations for wind farms. In each data layer, weights were given to every criterion based on eligible value for the wind farm site. The layers, criteria, or subclasses, and weights used in suitability analysis are presented in Table 8. The categorizing suitability maps were proposed to classify wind suitability. The ranked maps for classifying criteria were overlaid using the Analytical Hierarchy Process (AHP) method with their appropriate weight influence shown in Table 4. The detailed map based on the categorizing method is shown in Fig. 15. The share of suitability classes based on the categorizing integration methods is shown in Fig. 16.

6. Results and discussion

For site selection, a two-step approach of data integration is employed to display the data layers, criteria, and weights. The methodology (Fig. 5) and tools extended were utilized to accomplish multi-criteria wind farm site selection. The most relevant areas for final site selection were manifest.

6.1. Comparison with similar studies

This paper focuses on the best suitable areas for wind farm developments within Alborz Province with the suitability scores

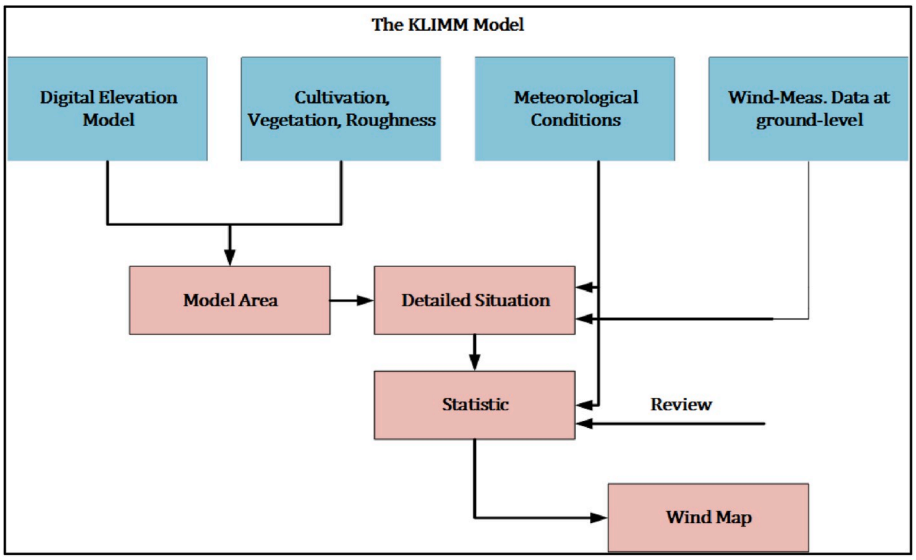


Fig. 11. The flowchart of the KLIMM model [6].

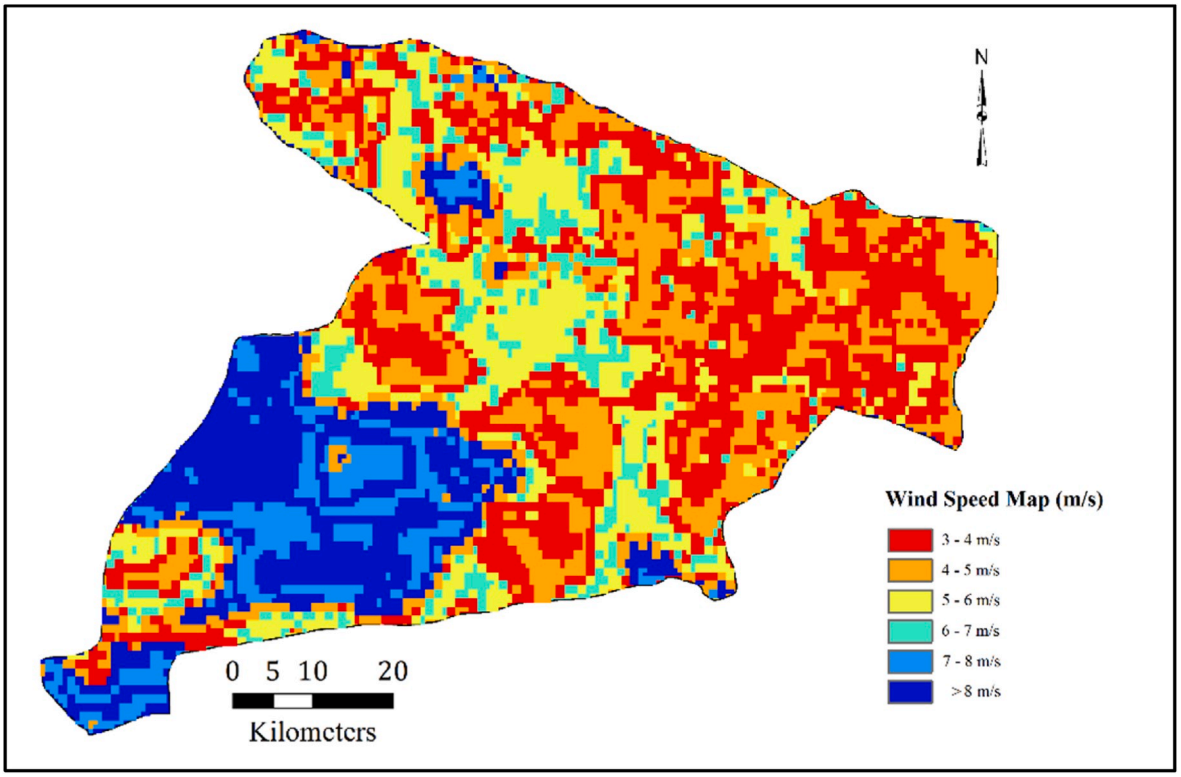


Fig. 12. Wind resources map of Alborz province.

Table 6
The slope of terrain sub-classes and their related areas [km^2].

Slope [%]	0–3	3–6	6–9	9–12	12–15	15–18	18–21	21–24	24–27	27–30	>30
Area Km^2	312.5	688.8	532.7	373.1	262.7	202.5	167.5	149.1	141.9	132.3	2158.2

comparative to the considered criteria and spatial scope of the region. Accordingly, the results are relatively equivalent to other wind farm site selection studies. For instance, wind energy potential criterion is regarded as the furthermost significant one; areas with the lowest total value scores in the rated area map are expected to be those with lower scores in the wind energy potential criterion. The wind speed, however, seems to be related to the height of elevation and the slope of the terrain. Compared to plane areas, elevated areas and steep slopes are inclined to have lower wind speeds. This is also observed in other studies [6,52,53]. In our analysis, this correlation is particularly obvious in the northern

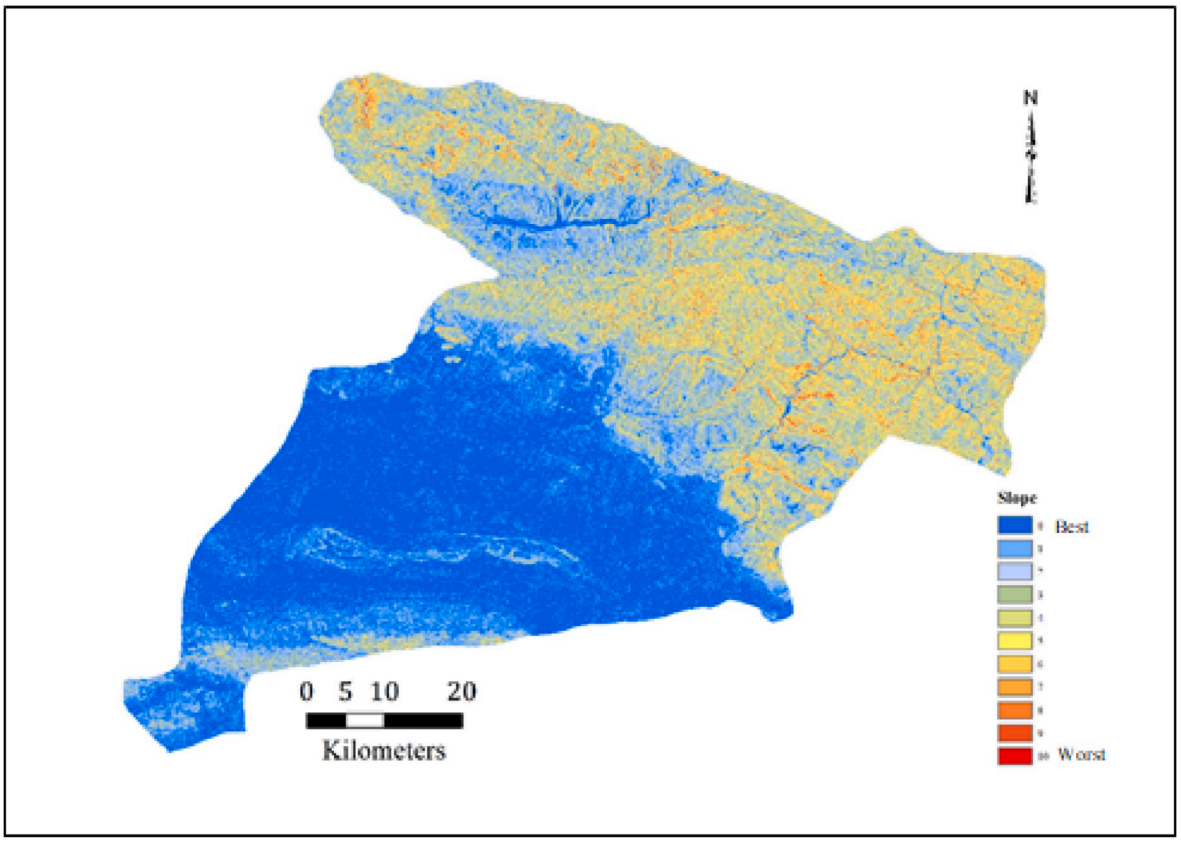


Fig. 13. Slope classified areas.

Table 7
Average prices for installation of posts with different capacities [2].

Number	The capacity of a post (kV)	Average price (s)
1	20	158
2	63	1850
3	132	735
4	230	998
5	400	2757

part of the region, where steep slopes and elevation cause the lowest wind speed of the region (see also Fig. 12).

The most significant difference between this study and other studies is considering electrical criteria as one of the main concerns in the AHP method. The Possible impacts of the wind farm on power networks are not considered in any of the previous research. Given that increasing levels of penetration of wind energy in electricity networks, it must be considered that the initial design of networks did not envision wind farm in the distribution system. The design of networks was based on more centralized generation sources feeding into the transmission system, then sub-transmission and distribution systems. The security, control, protection, power flows, and earthing of the network were predicated on a centralized generation model with a small number of source nodes, with communication and control linking major generators and nodes. When installing wind farms, shallow penetration (typically 5–10% of connected load) on a distribution system can generally be tolerated without significant problems. The threshold where problems occur depends heavily on the configuration of the network, length of lines involved (and hence impedances), and the concentration and time dependence of the load and generation in the area. Another factor is the financial aspect of building new power lines. If the distances of the wind farm from an existing high voltage power line do not come into considerations, the cost of building new electrical towers and power lines can even go higher than the wind farm itself.

6.2. Results

Diverse standards were used to outline proper sites. Fig. 7 demonstrates that structural criteria excluded 24% of the study area. The topographical and ecological criteria excluded about 55% and 42% of the study area is shown in Figs. 8 and 9, respectively. By directing the restrictive process, structural, topographical, and ecological criteria were utilized simultaneously, and inappropriate sites were outlined, which includes 80% of the study area.

The map of essential, topographical, and geological criterion and AHP criteria were overlaid by applying the intersection technique, and the final locations were classified. Fig. 17 presents the final suitable sites for wind farms in Alborz province, and Fig. 18 shows the share of each class in the study area. The categorizing method was employed, and the outcomes disclosed that 20% of the study area was suitable (Fig. 10) in eight classes (see Fig. 17).

The specific places were distinguished by overlaying the results of the restrictive and categorizing methods, and 20% of the study area was eventually outlined. Appropriate locations can be recommended to wind farm designers for establishing wind farms. Fig. 18 also shows the share of each class on the final suitability map.

7. Sensitivity analysis

The sensitivity analysis is conducted in previous studies in order to examine the suitability of assigned weights by consultants. Some studies only applied the same weights for all criteria [7]; however, some others benefited from the same weight for all AHP criteria and also removing some specific criteria to analyze the results [35]. In our case, we defined three scenarios to check the variations of final suitable maps and results fluctuations.

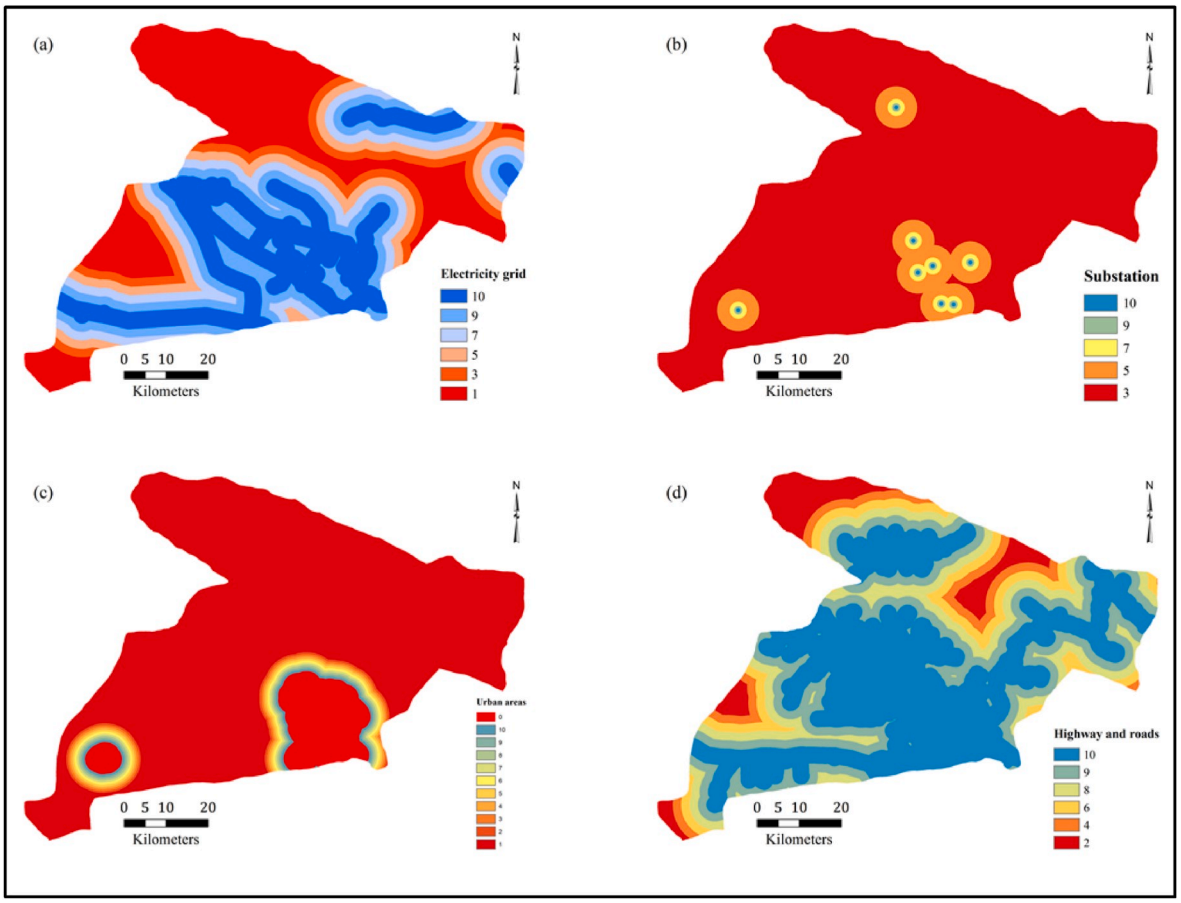


Fig. 14. Rated map of criteria (a) distance from electricity grid (b) distance from substations (c) distance from urban areas (d) distance from highways and roads (10 is the best, 0 is the worst layer).

Table 8
AHP criteria and assigned weights.

Weight	Geographical		Electrical		Economical	
	The slope of terrain [%]	Wind speed [m/s]	Distance from electricity grid [m]	Distance from substations [m]	Urban areas [m]	Highway and roads [m]
10	0–3	–	250–2000	250–500	2500–3000	500–2000
9	3–6	>8	2000–4000	500–1000	3000–3500	2000–4000
8	6–9	7–8	–	–	3500–4000	4000–6000
7	9–12	6–7	4000–6000	1000–2000	4000–4500	–
6	12–15	5–6		–	4500–5000	6000–8000
5	15–18	–	6000–8000	2000–5000	5000–5500	–
4	18–21	4–5	–	–	5500–6000	8000–10,000
3	21–24	3–4	8000–10,000	>5000	6000–6500	–
2	24–27	–	–	–	6500–7000	>10,000
1	27–30	–	>10,000	–	7000–7500	–
0	>30	0–3	<250	0–250	>7500	0–500
References	[7]	–	[6]	[2]	–	[6]

Scenario (1): Assign the same weights for all AHP criteria (in our case, 16.67% for each criterion).
Scenario (2): Assign zero weight to two economic criteria (distance from urban areas and highways and roads).
Scenario (3): Assign zero weight to two electrical criteria (distance from power lines and substations).

In scenarios (2) and (3), all the pair-wise comparison matrixes remained unchanged, and the weights have been calculated again. Fig. 19 shows the final map of suitable sites after conducting the three defined scenarios. The outcomes of the sensitivity analysis are shown in Table 9. Moreover, Table 9 shows the discrepancy in the amount of land accessible per class among the results attained from the AHP model and the sensitivity analysis.

The results indicate that the variance of suitable land for the high favored classes is different for each scenario. Applying equal weights to the criteria indicates that the area of the highly preferred classes (7–9, which are the best classes in the case study area) will diminish, and low favored classes increase. However, in the second scenario (no economic criteria), the condition for the desired classes is entirely different, and they enjoy a definite number increase, which means the area in these classes is increased by eliminating the economic criteria. The maximum change for suitability class 9 (which is the best class in this study) occurs in scenario (2). On the other hand, eliminating the electrical criteria is the best way to enhance the area of available land for wind farm developments on account of its highest effect on high favored classes.

Table 9
Suitable areas in Alborz Province according to the AHP and sensitivity analysis results.

Suitability classes	AHP		Equal weights		No economic criteria		No electric criteria	
	[km^2]	[Δ]	[km^2]	[Δ]	[km^2]	[Δ]	[km^2]	[Δ]
9	14	0.23	2	−12	43	29	15	1
8	174	1.65	22	−152	179	5	356	182
7	209	3.07	178	−31	151	−58	271	62
6	304	20.48	326	22	360	56	120	−184
5	193	32.31	289	96	137	−56	134	−59
4	29	22.22	97	68	44	15	36	7
3	16	18.53	21	5	18	2	7	−9
2	2	1.51	6	4	9	7	2	0
Total suitable area	941	–	941		941		941	

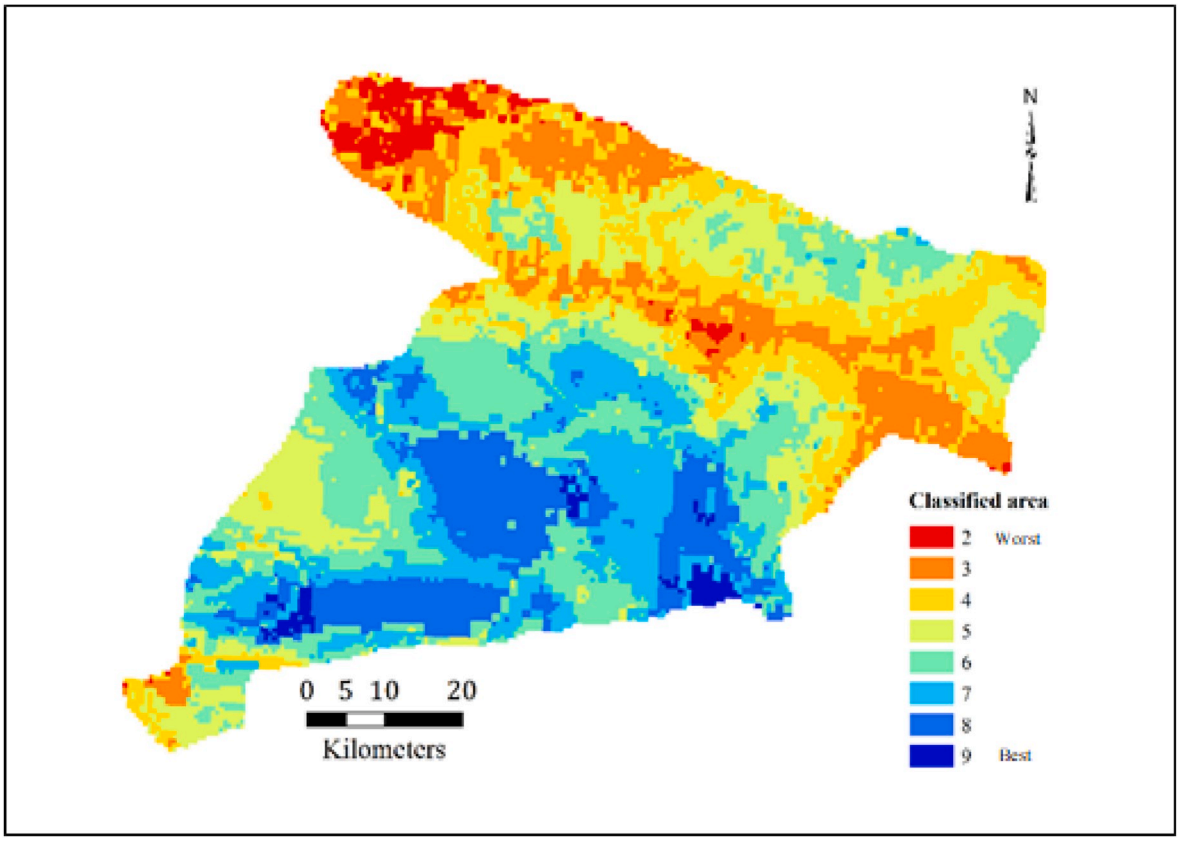


Fig. 15. Classified areas based on the categorizing method.

Therefore, the elimination of electrical criteria will be the best way to increase potential areas.

8. Conclusions

The study applied the Multi-Criteria Decision Making (MCDM) for distinguishing proper sites for the Alborz province, Iran. The initial phase of this procedure was to eliminate all areas which are constricted because of legitimate limitations and authentic logics. In the next phase, a detailed map of the area was generated, exposing the judgment of the specialists. The last phase of the study was to detach the exclusion area from the classified area, and to categorize the suitable areas, according to the weights they have attained. ArcGIS was conducted to reveal and visualize the results.

The strengths of the method used in this study are its usability. It unravels a disorderly problem by splitting it into smaller phases and does not necessitate genuine data sets. The construction of AHP produces a humble path for a scholastic individual to take care of intricate issues. On the other hand, the weakness of AHP is its utilization of fundamental qualities for judgments, and for future research in this area, FUZZY AHP can overcome this weakness.

The proposed outline selected structural, topographical, and ecological limitations and integrated them with electrical, practical, and economic criteria to raise the specific sites that are entirely suitable for wind farm site selection. For this purpose, based on these limitations and criteria, a classifying map has been created to define final sites. It was discovered that 20% of the Alborz province is suitable for wind farm development. The outcome of the study shows that the South East area of the province (including Karaj and Nazar Abad County) has the highest priority in Alborz province. It can be concluded that 80% of the area is unsuitable. The four dominant suitable classes are suitability classes 5, 6, 7, and 8 with 193 km^2, 304 km^2, 209 km^2, and 174 km^2, respectively.

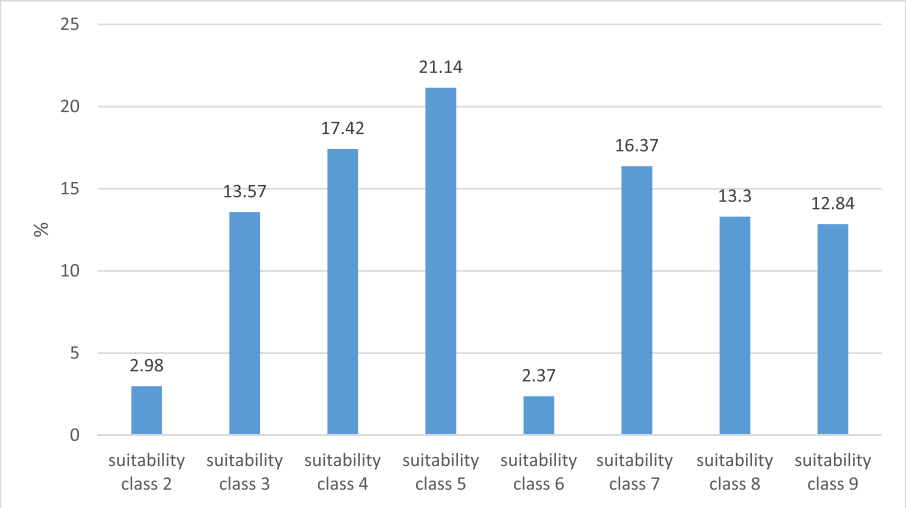


Fig. 16. The share of suitability classes based on the categorizing method.

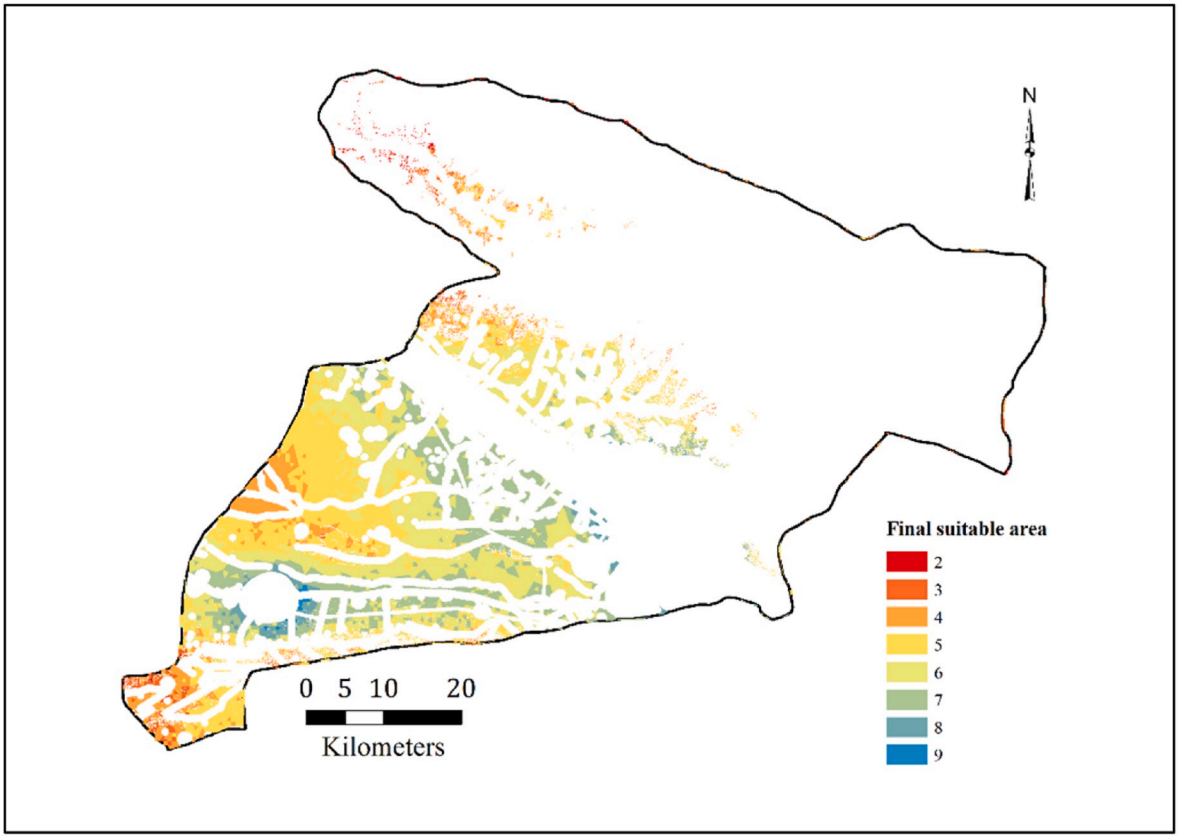


Fig. 17. Final suitability map (9 is the best, 0 is the worst layer).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Siamak Moradi: Data curation, Writing - original draft, Conceptualization, Methodology, Software, Writing - review & editing, Visualization, Formal analysis. **Hossein Yousefi:** Supervision, Methodology, Conceptualization, Writing - review & editing. **Younes Noorollahi:** Data curation. **Diego Rosso:** Supervision, Writing - review & editing.

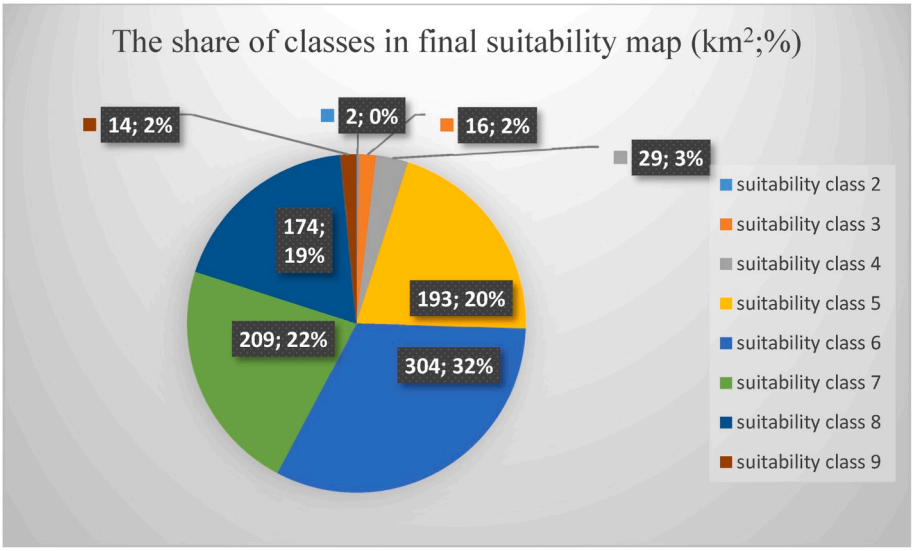


Fig. 18. The share of classes in the final suitability map.

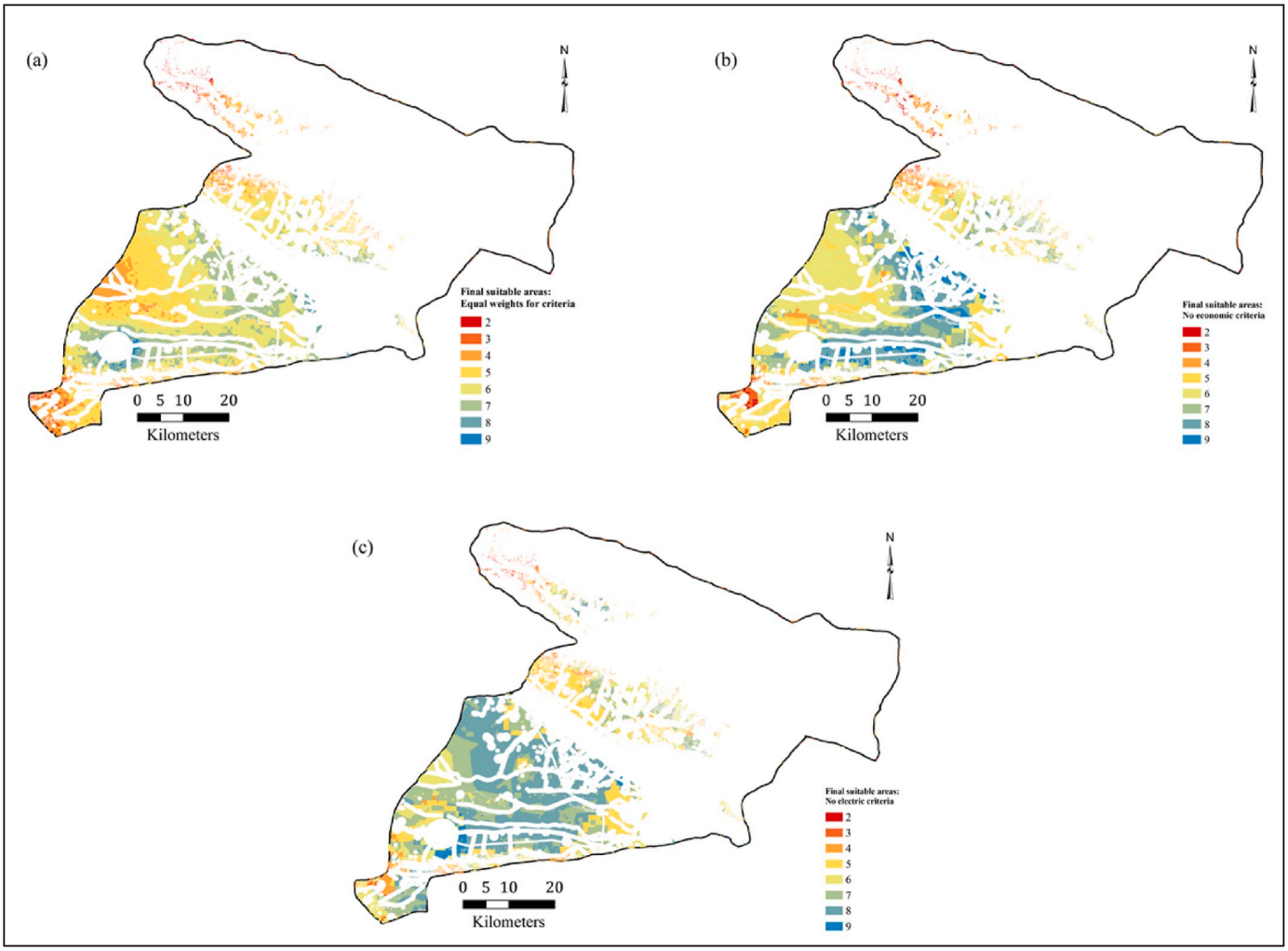


Fig. 19. Sensitivity analysis of results: (a) scenario 1 (b) scenario 2 (c) scenario 3 (9 is the best, 0 is the worst layer).

Appendix A

Table 10
Survey Participants.

	Individuals	Organization
1	Prof. Diego Rosso	The University of California, Irvine, USA
2	Sajjad Mohammadi (Ph.D.)	Massachusetts Institute of Technology (MIT), USA
3	Prof. Youness norollahi	University of Tehran, Iran
4	Prof. Vahid Abbasi	Kermanshah University of Technology, Iran
5	Prof. Alireza Aslani	University of Tehran, Iran
6	Amin Yousefi-Sahzabi (Ph.D.)	Kyushu University, Japan
7	Rozbeh Abbassi (Ph.D.)	UNSW, Sydney, Australia
8	Mohsen Kheirabadi (MS)	University of Connecticut, Connecticut, USA

Note: Opinions expressed by individual experts do not necessarily coincide with the opinions of the institutional bodies concerned.

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