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Multi-Criteria Decision-Making System for Wind Farm Site-Selection Using Geographic Information System (GIS): Case Study of Semnan Province, Iran

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Abstract: Selecting the best place for constructing a renewable power plant is a vital issue that can be considered a site-selection problem. Various factors are involved in selecting the best location for a renewable power plant. Therefore, it categorizes as a multi-criteria decision-making (MCDM) problem. In this study, the site selection of a wind power plant is investigated in a central province of Iran, Semnan. The main criteria for classifying various parts of the province were selected and pairwise compared using experts' opinions in this field. Furthermore, multiple restrictions were applied according to local and constitutional rules and regulations. The Analytic Hierarchy Process (AHP) was used to weigh the criteria, and according to obtained weights, wind speed, and slope were the essential criteria. Moreover, a geographic information system (GIS) is used to apply the weighted criteria and restrictions. The province's area is classified into nine classes according to the results. Based on the restrictions, 36.2% of the total area was unsuitable, mainly located in the north part of the province. Furthermore, 2.68% (2618 km^2) and 4.98% (4857 km^2) of the total area are the ninth and eightieth classes, respectively, which are the best locations for constructing a wind farm. The results show that, although the wind speed and slope are the most essential criteria, the distance from power facilities and communication routes has an extreme impact on the initial costs and final results. The results of this study are reliable and can help to develop the wind farm industry in the central part of Iran.

Keywords: wind farm site selection; multi-criteria decision-making system; Analytic Hierarchy Process; Semnan province; ArcGIS

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1. Introduction

In recent years, environmental problems, such as global warming, climate change, pollution, and problems with traditional fossil resources (such as increased extraction costs and non-renewability) that have been a source of human energy for many years, have caused doubt about the use of these resources and increased the tendency to employ more renewable resources [1]. Countries ratified the Paris Climate Agreement in 2015 to control this critical situation. Under the agreement, Iran voluntarily pledged to reduce greenhouse gas emissions by 4% and 8% by 2030 and 2050, respectively [2]. Using renewable energy resources, such as solar, wind, waves, and biofuels, play a crucial role in reaching this goal.

Utilizing wind energy can play an important role in enabling Iran to meet the standards set for this country in the Paris Agreement. Studies have also shown that hybridizing wind turbines with other energy sources reduces carbon emissions [3]. Applying wind energy creates employment and helps reduce CO_2 [4]. Research shows that wind energy use in Canada, Sweden, China, and Germany will increase significantly by 2025 [5]. Meanwhile, it has a more extended history than other renewable sources in Iran. It is also low-cost and attractive to investors and can reduce dependence on fossil fuels [6].

Wind energy also has adverse effects, such as noise, unpleasant visual impact (tourism industry), habitat occupation, and the extinction of some bird species [7]. Therefore, it is necessary to minimize these adverse effects according to the existing criteria for locating and constructing wind farms.

MCDM is a method to evaluate multiple conflicting criteria in decision-making problems. MCDM could be applied for various applications, some of which are mentioned in references [8–10]. In addition, it is a suitable solution to deal with different and sometimes contradictory criteria for choosing the best places to use renewable resources [11]. There are several methods for weighing criteria in MCDM. Some of these methods include AHP [12], analytic network process (ANP) [13], fuzzy measures [14], Entropy [15], Swara [16], Dematel [17], Standard deviation [18], etc.

The ANP is a generalization of AHP. ANP is used to solve more complex decision-making problems, which AHP is not suitable for solving [19]. According to some scientists, the use of an exact number to compare the alternatives, unbalanced scale of judgment, inability to manage uncertainty, and inaccuracy in pairwise comparisons have caused some doubts about AHP [20,21]. Nevertheless, it is no secret that AHP is one of the most essential and widely used methods in MCDM. In some papers, due to interval judgment instead of fixed judgment [22], the Fuzzy AHP method is used to weigh the criteria. In 2021, Nguyen et al. used a hybrid fuzzy AHP MCDM to organize the priorities of the medical community and government during the COVID-19 crisis in Vietnam [23]. In another study by Nguyen, fuzzy AHP and machine learning approaches were used to predict vaccination intention against COVID-19 [24]. Entropy is another weighing method that has been widely used in recent years. The main difference between Entropy and other methods is to remove the human factor from the decision-making process [25], which enhances this method's accuracy. In 2015, Zhao and Gou developed a hybrid MCDM system based on Entropy to evaluate China's economic, social, and environmental benefits of the renewable energy sector [26]. In other studies, MCDM systems based on Entropy were used to investigate the sustainable development factors worldwide [27–30]. There are two general views on the Entropy method. According to some literature, Entropy is reliable and effective [31]. However, from the other point of view, Entropy results do not always consider the importance of the indexes [32]. The Swara method is similar to AHP in that the expert's opinion specifies the importance and prioritization of the alternatives. In the end, the weight of the attributes calculates by considering two main features. According to this method, all the attributes are compensatory and independent [16]. The Dematel is similar to Swara, except that Dematel is used to solve very complex subjects. In the decision-making process of Dematel, the expert's opinion uses to develop the pairwise comparison matric, and it has three main features. The attributes are compensatory and independent from each other. The qualitative attributes convert to quantitative attributes [16]. Moreover, the Swara and Dematel methods have been extensively used in MCDM problems, especially in the renewable energy sector [33–35]. In this study, the AHP method was used to solve the site-selection problems due to following reasons:

1. It is widely used because it is easy to understand and apply.
2. It is very compatible with GIS which is extensively used for land analysis and site-selection problems.
3. Possibility of hierarchical modeling, adoption with verbal judgments, and consistency verification [36].
4. AHP can be combined with other methods, including mathematical programming, fuzzy sets, genetic algorithms, neural networks, etc. [36].
5. It considers both quantitative and qualitative criteria to interpret the problem [37].
6. AHP can apply various sensitivity analyses to criteria [38].
7. AHP facilitates the decision-making process, using the pairwise comparison among the criteria [38].
8. AHP can consider the consistency and inconsistency of the alternatives, which is one of the essential benefits of this method [38].

9. In site-selection problems, where the main goal is to select the best places, simple methods such as AHP are sufficient, and more complicated methods such as fuzzy AHP do not necessarily lead to different results [39].

In this study, GIS is employed to create and use map layers. GIS is a powerful tool for MCDM, and it can utilize topological, structural, and ecological information to perform calculations based on criteria and sub-criteria. Topological, structural, and ecological information can be displayed as layers in GIS, and by overlapping these layers, criteria, and restrictions, the final suitable and inappropriate locations can be determined. Afterward, a suitable area can be weighed according to various criteria. These criteria are determined by the type of problem and the area. After classifying the suitable areas according to these criteria, the importance and value of each area were determined, and decision-making was carried out according to the categorized final map. Figure 1 illustrates how the GIS tool works in integrating information layers.

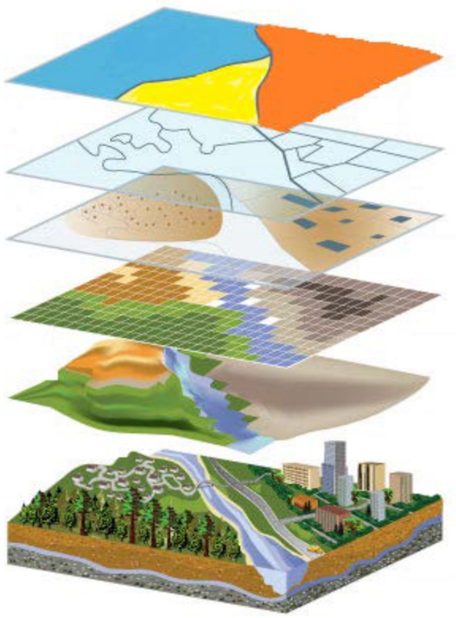


Figure 1. Integrating information layers using GIS [40].

2. Literature Review

GIS is widely applied in site selection issues. Xu et al. [41] used GIS, Interval Analytic Hierarchy Process (IAHP), and stochastic VIKOR to find the best area for wind farms in the Wafangdian region, China. Colak et al. [42] also employed GIS and AHP to find an optimal area for a photovoltaic farm in Malatya, Turkey. Castro-Santos et al. [43] studied Galicia coastal area in Spain for floating offshore wind farm site selection via GIS. In addition to its application in selecting optimal areas for renewable energy farms, GIS is used for rainwater harvesting [44], power plants [45], landfills [46], pressurized irrigation [47], and electric vehicle charging stations [48] site selection.

Many articles have been published related to wind farm site selection using GIS in Iran. Moradi et al. [38] measured wind energy potential in Alborz province (central regions of Iran) through MCDM and GIS. They used AHP to weigh the criteria, and according to their results, 20% of the area was suitable for wind farms. Noorollahi et al. [6] conducted the same work for Markazi province (west of Iran), and based on the results, 28% of the area was suitable for wind farms. In 2020, in a study by Ahmadi et al. [49], different parts of Iran were reviewed to build a wind-powered pump storage plant, and according to the results, the Gilane-Gharb dam was the best area and the capacity of which was estimated at 31 MW.

Table 1 represents several other studies on wind farm site selection in Iran and other countries.

Table 1. Other renewable resources site selection research in Iran and other countries.

Ref	Location	Type of Site Selection	Applied Method
[50]	Shahrood, Khorramdareh, Zabol, and Abadeh In Iran	Wind farm	TOPSIS
[51]	Izmir, Turkey	Wind farm	MCDM-(best-worst method) (BWM)
[52]	Northeast of Iran	Wind farm	Equal importance criteria
[53]	China	Offshore wind farm	MCDM-intuitionistic linguistic aggregation operators
[54]	China	Wind farm	MCDM-Fuzzy
[55]	India	Wind farm	MCDM-Fuzzy AHP
[56]	Sudan	Wind farm	MCDM-Fuzzy AHP
[57]	Mauritius	Wind farm	MCDM-AHP

One of the main practical uses of the decision-making systems is to improve risk assessment ability and overcome the adverse effects [58] of the site-selection projects. Multi-dimensional assessment and making accurate decisions are vital prerequisites to starting a business. Moreover, location selection is one of the essential parts of the business due to the long-term impacts on risks and costs of the projects [59]. Furthermore, as another practical benefit of decision-making systems, the simultaneous use of GIS and MCDM reduce the cost and time of the site-selection problems and increases the accuracy. At the same time, GIS-MCDM-based decision-making systems take multiple environmental, social, economic, and sustainability parameters to account to make the best decision among the various alternatives [60].

This research aimed to determine the suitable area for wind farms in Semnan province, Iran. Semnan has the lowest population density among the provinces of Iran and is also the seventh province in terms of area. Moreover, due to unfavorable climatic conditions, the possibility of agriculture is less in many parts of Semnan province, such as the southern areas. Therefore, there is much usable land in many parts of the province. Semnan province is also one of the central provinces of Iran, located near the capital (Tehran) and other large provinces, such as Khorasan and Isfahan. The proximity of the province to energy highways and energy consumption centers increases the importance of this strategic province for energy production. The construction of fossil power plants, such as steam, combined cycle power, and plants, seems very irrational due to high water consumption, pollution, and contradiction with the hot and dry climate of the province. For the above reasons, renewable sources, namely wind energy, seem a very reasonable and justifiable option. Criteria and sub-criteria were specified to evaluate the wind farm potential in the province. To solve this decision-making problem, AHP will be applied to weigh and compare the criteria. The main selected criteria for this study are wind speed, slope, power lines, power stations, urban areas, highways, and roads. These criteria were chosen according to similar previous studies and the opinion of the experts. Finally, areas with the most potential for the wind farm will be specified separately. In Section 3, the study area, electricity consumption, and social information of the Semnan are described. In Section 4, the AHP method is presented, and the weights of the criteria will be calculated. In Section 5, the weighted criteria and multiple restrictions will be applied. In Section 5, the final categorized map will be presented using the data of previous sections, and the results will be discussed and compared with other papers.

3. Study Area

Semnan is one of the central provinces of Iran, located in the east of Tehran province, south of the Alborz mountains, and north of Dashte-e kavir. This province is centered in Semnan city, and Shahrood, Garmsaar, and Damqaan are the other important cities of Semnan province (Figure 2). The province covers an area of 97,491 square kilometers, which is 5.9% of the country's total area. This province is the seventh province in Iran in terms of area. In the last official census in 2016, the province's population was 702,000, and the relative population density was 2.7 people per km^2. This vast province is home to less than one percent of the country's population [61].

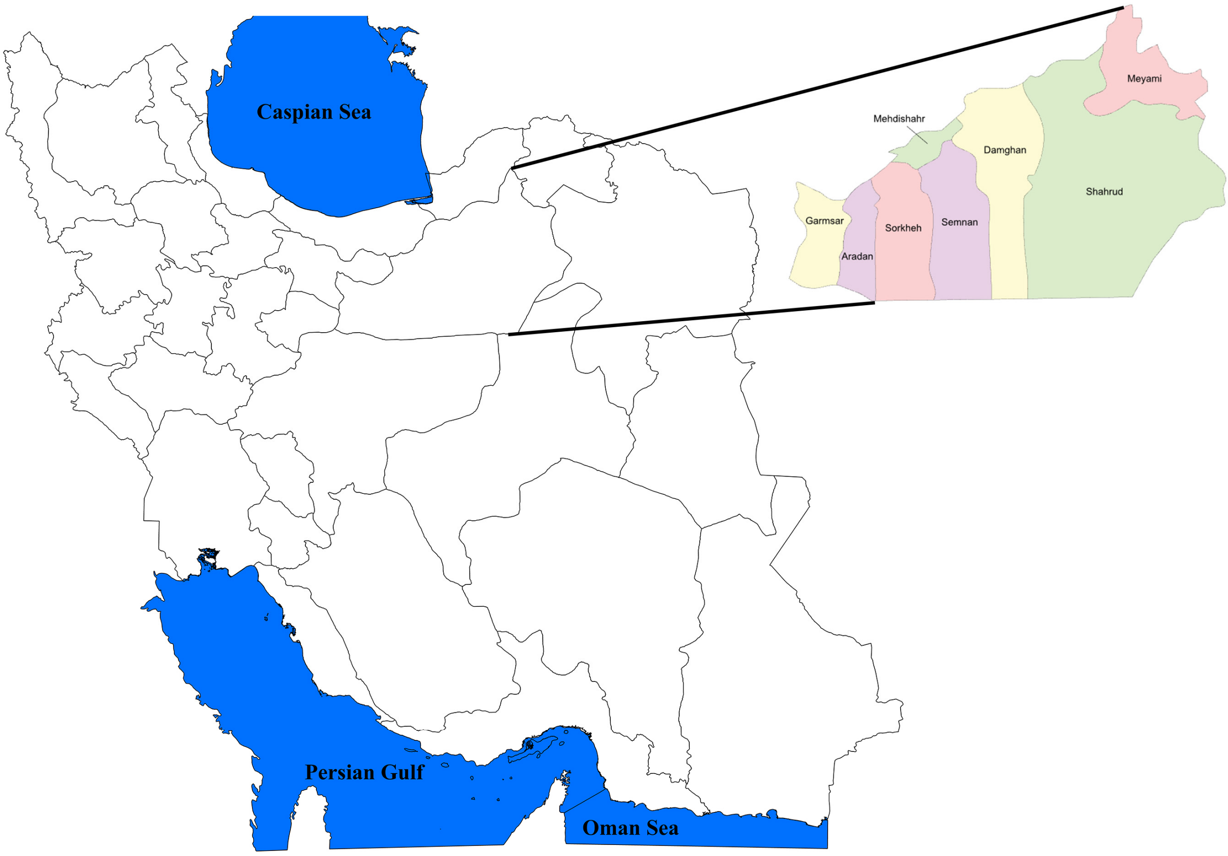


Figure 2. Location of Semnan in Iran map.

With an average daily temperature of 24 °C and a maximum temperature of 39 °C, Semnan is considered a warm province. The best months to travel to Semnan are June to September, and the worst months are November to March [62].

Iran's electricity grid has expanded considerably in recent decades, and most of the electricity generation in this grid is provided by fossil thermal power plants. According to the pattern obtained in the last decade, electricity consumption in Iran is increasing by 6% annually. Figure 3 depicts the trend of the increase in electricity production and consumption in Iran's electricity grid from 1980 to the last decade. According to this figure, the electricity network will face several problems in supplying electricity in the near future.

Semnan has two large power plants named Shahid Bakeri and Shahid Bastani, whose net production in 2018 was equal to 2,433,779 MWh. In 2018, out of 377,050 electricity subscribers in Semnan province, 76.88% were household, 13.69% commercial, 1.62% agricultural, 5.88% general, 1.32% industrial, and 0.58% street lighting. Moreover, 20.19% of the total electricity sold was for household consumption, 8.69% for general consumption, 23.28% for agricultural consumption, 40.3% for industrial consumption, 5.21% for commercial consumption, and 2.33% was allocated to street lighting. Figure 4 demonstrates the amount of electricity sold to various subscribers in 2018 [64,65].

Based on the annual consumption pattern, electricity consumption in Semnan is growing every year, and wind resources can be a key to meeting this demand.

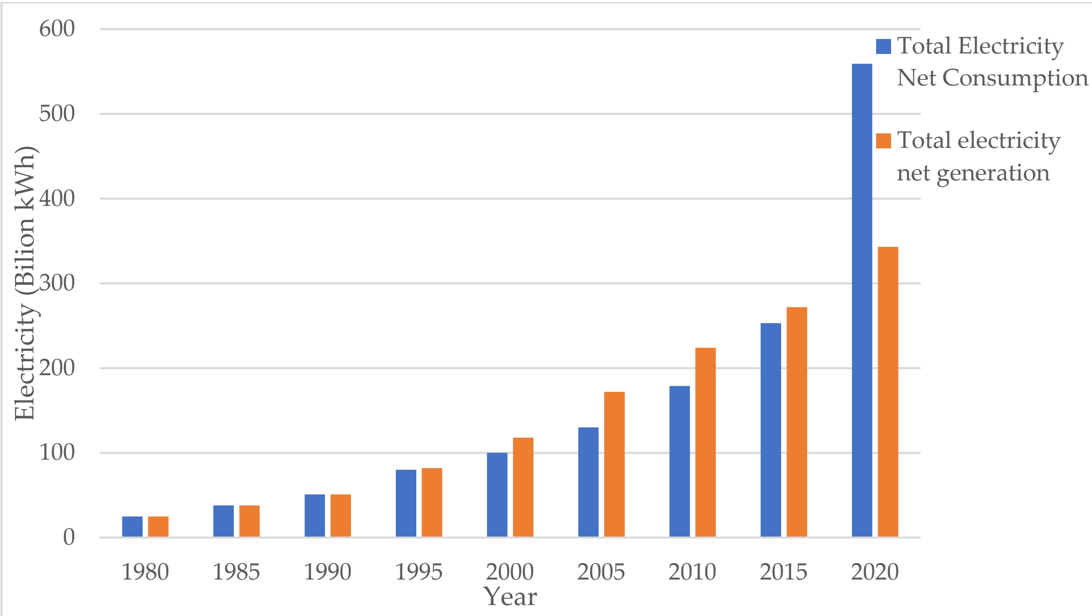


Figure 3. Electricity production and consumption growth in Iran (based on the data from [38,63]).

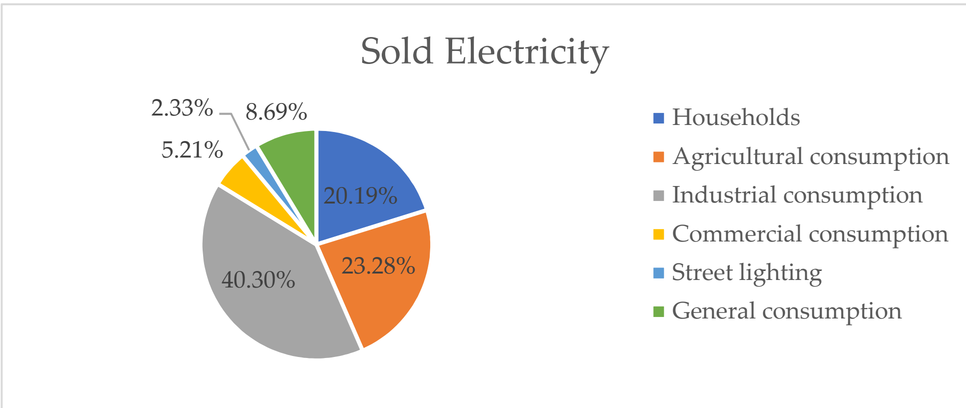


Figure 4. Electricity consumption of different groups of subscribers in Semnan [64,65].

4. Analytical Hierarchy Process

MCDM techniques are applied to solve site selection problems [66]. AHP is one of the most widely used methods in MCDM, introduced by Saaty in 1980 [12]. One of the advantages of AHP is the pairwise comparison among the criteria of the problem. Through this method, sensitivity analysis can be carried out on the criteria and sub-criteria by offering several choices. AHP can minimize the impact of taste decisions and orientations in problem-solving, which is another important advantage of this method [38].

In the AHP method, the problem becomes hierarchical, consisting of four levels. These levels are the problem goal, the criteria, the sub-criteria, and the final choices [67,68].

In the AHP method, the criteria are compared two by two. To compare the criteria, they are given points ranging from one to nine, which can be seen in Table 2 [12,69,70].

Thus, the adjustment ratio (CR), indicating the degree of coherence of decision makers' opinions, is calculated according to Equation (2). The appropriate value for CR is below 0.1, and if it exceeds this value, decision-makers should reconsider their views in pairwise comparison. If the pairwise comparison does not involve inconsistencies, the principal eigenvalue (λ_{max}) is at least the same as the number of columns or rows ($\lambda_{max} = n$) [38].

Table 2. Pairwise comparison scales in AHP [69].

Scale	Numerical Rating	Reciprocal
Extreme importance	9	1/9
Very to extremely strong importance	8	1/8
Very strong importance	7	1/7
Strong to very strong importance	6	1/6
Strong importance	5	1/5
Moderate to strong importance	4	1/4
Moderate importance	3	1/3
Equal to moderate importance	2	1/2
Equal importance	1	1

Consistency index (*CI*) could be calculated from Equation (1) [12]:

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

The consistency ratio (*CR*) is calculated from Equation (2):

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

Table 3 represents the Random Index (*RI*) values used to calculate *CR*. As mentioned, the *CR* value should be less than 0.1. Otherwise, the decisions made in the pairwise comparison should be reconsidered [71].

Table 3. Random index values according to Saaty and Tran [70].

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

The suggested criteria for this decision-making problem are wind speed, slope, distance from power lines, distance from substations, distance from highways and roads, and urban areas. Figure 5 portrays the decision process hierarchy for the wind farm.

All of the criteria were compared, the weight of each was determined, and incompatibility rate calculations were performed for the criteria. Table 4 shows a pairwise comparison of the criteria for selecting wind farm locations. Some university experts made this pairwise comparison. Appendix A (Table A1) shows the academic information of these experts.

As can be seen in Table 4, wind speed is an essential criterion, and investigating the wind speed of the study area could help to estimate the wind power potential, and larger wind turbines can be installed to generate more power in areas with higher wind energy potential. Lands with lower slopes are usually prioritized. Because increasing the slope can increase the initial cost of construction and the maintenance cost. The distances from power lines and power stations also have a direct impact on the project cost. In remote areas that do not have access to the facilities of the electricity network, the construction of power stations and lines can incur huge initial and maintenance costs to project investors. Moreover, the remoteness of urban areas, roads, and highways could cause higher investment costs, such as constructing new access roads. Remoteness from urban areas, where most of the electricity consumption occurs, can also be technically problematic. Because increasing the distance between power the producer and consumer and lengthening the power transmission lines will cause more voltage drop and power loss, and maintenance of these long power transmission lines can be tedious and costly.

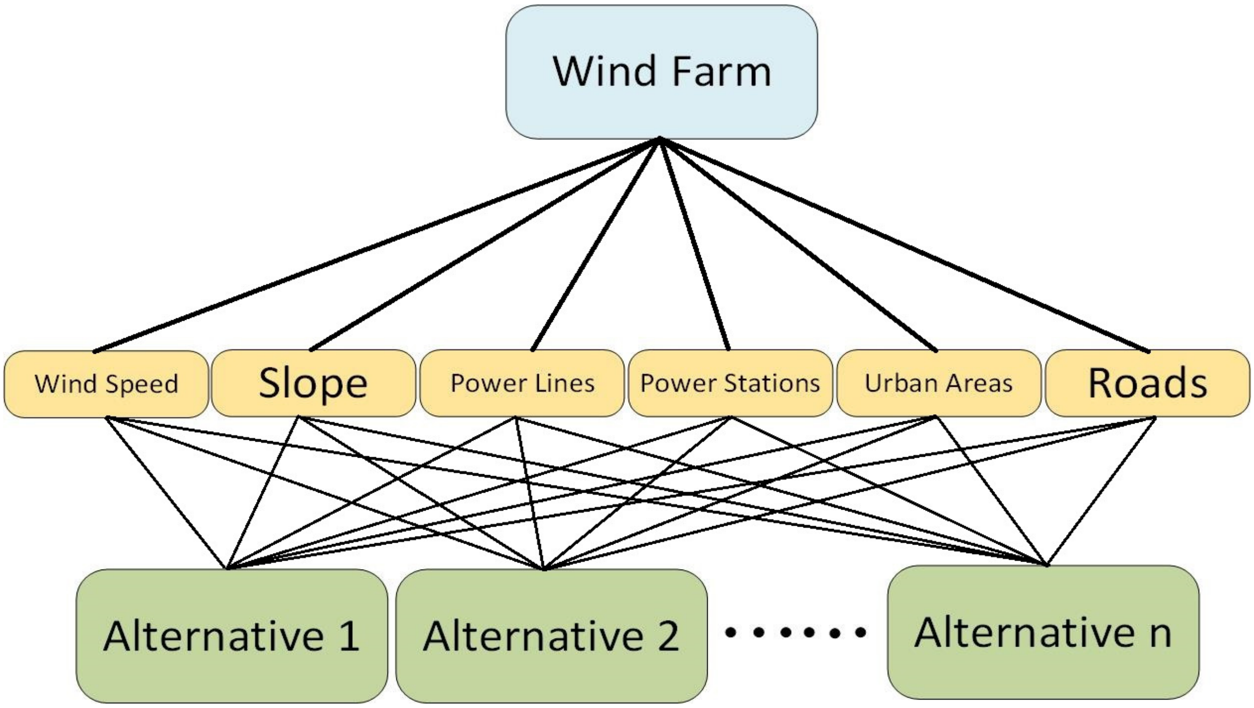


Figure 5. Decision process hierarchy for wind farm.

Table 4. Pairwise comparison for wind farm.

Criteria	Wind Speed	Slope	Power Lines	Power Stations	Urban Areas	Highways	Roads
Wind Speed	1	2	3	3	2	3	3
Slope	0.5	1	2	2	1	2	2
Power Lines	0.33	0.5	1	0.5	2	2	2
Power Stations	0.33	0.5	2	1	2	2	2
Urban Areas	0.5	1	0.5	0.5	1	1	1
Highways	0.33	0.5	0.5	0.5	1	1	1
Roads	0.33	0.5	0.5	0.5	1	1	1

Table 5 represents the pairwise comparison matrix that is calculated using the pairwise comparison of the criteria shown in Table 4. The last row of this matrix shows the sum of each column. Table 6 represents the normalized pairwise matrix calculated by dividing each element of Table 5 by its last row number. The last column of Table 6 shows each criterion weight from the average of each row of the normalized matrix. In the next step, the consistency of the AHP results investigates using the CR value. Table 7 represents the consistency matrix. The last row of this matrix represents the weight of each criterion. The elements of this matrix calculate by multiplying the elements of each column of Table 5 by that column's weight. Furthermore, one of the columns of Table 7 shows the weighted sum value, which shows the sum of each row of consistency matrix elements. The last column of Table 7 shows the ratio of weighted sum value to weights in each row. λ_{max} calculates by averaging the numbers of the last column of Table 7, which is equal to 7.29. Finally, CI and CR calculate using Equations (1) and (2) [24].

Table 5. Pairwise comparison matrix of the MCDM problem.

Criteria	Wind Speed	Slope	Power Lines	Power Stations	Urban Areas	Highways	Roads
Wind Speed	1	2	3	3	2	3	3
Slope	0.5	1	2	2	1	2	2
Power Lines	0.33	0.5	1	0.5	2	2	2
Power Stations	0.33	0.5	2	1	2	2	2
Urban Areas	0.5	1	0.5	0.5	1	1	1
Highways	0.33	0.5	0.5	0.5	1	1	1
Roads	0.33	0.5	0.5	0.5	1	1	1
Sum	3.32	6	9.5	8	10	12	12

Table 6. Normalized pairwise comparison matrix of the MCDM problem with the weights of the criteria.

Criteria	Wind Speed	Slope	Power Lines	Power Stations	Urban Areas	Highways	Roads	Weights
Wind Speed	0.3012	0.3333	0.3157	0.375	0.2	0.25	0.25	0.2893
Slope	0.1506	0.1666	0.2105	0.25	0.1	0.1666	0.1666	0.1730
Power Lines	0.0993	0.0833	0.1052	0.0625	0.2	0.1666	0.1666	0.1262
Power Stations	0.0993	0.0833	0.2105	0.125	0.2	0.1666	0.1666	0.1502
Urban Areas	0.1506	0.1666	0.0526	0.0625	0.1	0.0833	0.0833	0.0998
Highways	0.0993	0.0833	0.0526	0.0625	0.1	0.0833	0.0833	0.0806
Roads	0.0993	0.0833	0.0526	0.0625	0.1	0.0833	0.0833	0.0806

Table 7. Consistency matrix of the criteria with the weighted sum value.

Criteria	Wind Speed	Slope	Power Lines	Power Stations	Urban Areas	Highways	Roads	Weighted Sum Value	Weighted Sum Value/Weights
Wind Speed	0.2893	0.346	0.3786	0.4506	0.1996	0.2418	0.2418	2.1477	7.423
Slope	0.1446	0.173	0.2524	0.3004	0.0998	0.1612	0.1612	1.29265	7.471
Power Lines	0.0954	0.0865	0.1262	0.0751	0.1996	0.1612	0.1612	0.905269	7.172
Power Stations	0.0954	0.0865	0.2524	0.1502	0.1996	0.1612	0.1612	1.106569	7.3668
Urban Areas	0.1446	0.173	0.0631	0.0751	0.0998	0.0806	0.0806	0.71685	7.1823
Highways	0.0954	0.0865	0.0631	0.0751	0.0998	0.0806	0.0806	0.581169	7.209
Roads	0.0954	0.0865	0.0631	0.0751	0.0998	0.0806	0.0806	0.581169	7.209
Weights	0.2893	0.173	0.1262	0.1502	0.0998	0.0806	0.0806		$\lambda_{max} = 7.29$

After performing the calculations, each criterion's final weights were obtained in the AHP method, as shown in Figure 6. The CR factor for this weighted criterion was 3.58%, implying that the pairwise comparison matrix is suitable and does not require change.

According to Figure 6, the most significant criterion is wind speed, which was predictable. After wind speed, the slope of the terrain, distance from power stations, distance from power lines, distance from urban areas, and distance from highways and roads are respectively important.

After calculating the weights, the buffer areas will be applied considering multiple restrictions. These restrictions include the distance from communication routes and railways, urban areas, and environmentally restricted areas. Moreover, according to the references, high-altitude lands specify as a buffer area due to the high cost of the construction process. These restrictions were taken into account by considering international and national standards and regulated technical, electrical, environmental, and economic principles. Figure 7 exhibits the methodology of the present paper. The various section of this study, including categorizing the study area using AHP weights and finding restricted areas, are shown in this figure. Finally, the final map can be obtained by overlying the categorized and restricted maps of the study area.

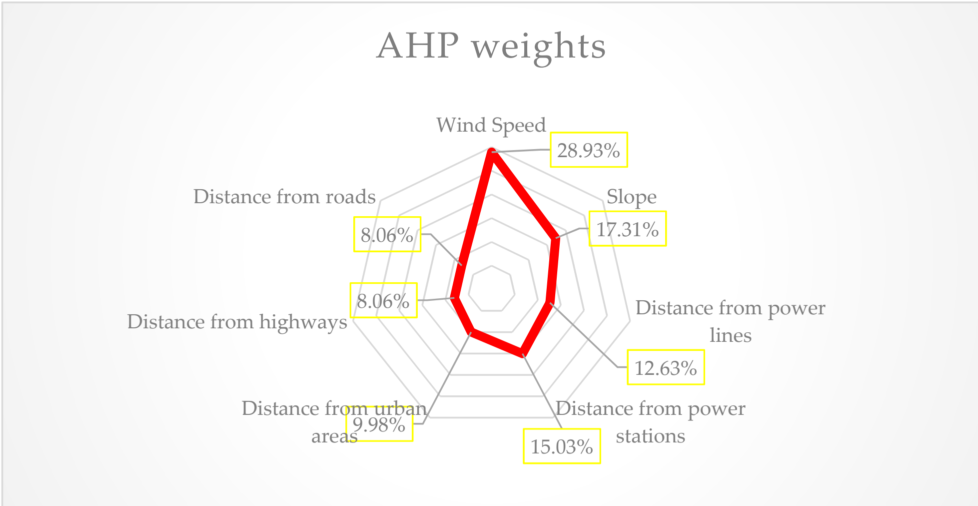


Figure 6. Final criteria weights according to the AHP method (CR = 3.7%).

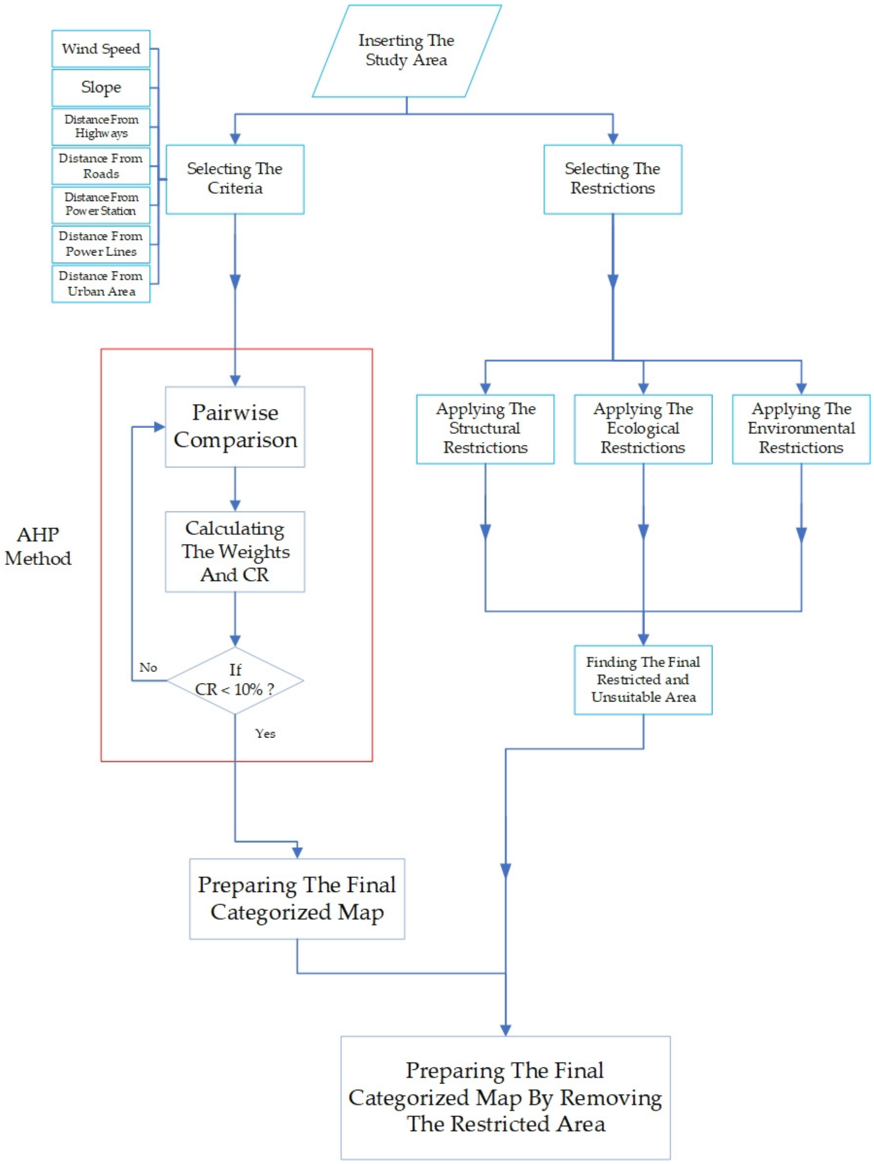


Figure 7. Methodology of study.

5. Materials and Methods

Selecting appropriate points for wind farm site selection is a complex process. The methodology for selecting suitable areas is determined by the calculated weights and the restrictions specified for ecological, structural, and topological criteria and sub-criteria.

A two-step methodology has been used to select the best areas for wind farms:

1. The province has been divided into two areas according to restrictions, suitable and unsuitable.
2. The best areas have been chosen according to the weighted criteria among suitable regions.

In the first step, some restrictions are applied to divide the province into two suitable and unsuitable parts. The restrictions are set for the amounts and distances of each topological, ecological, and structural features.

A conceptual model will be developed after dividing the province into suitable and unsuitable areas. Figure 7 depicts the conceptual model for this study. Specific criteria and restrictions are defined in this model. The required data, assessments, and the characterizations of the study area are collected. According to the defined criteria and collected data, the map layer will identify, layers will integrate based on the conceptual model, and the final suitable and the unsuitable area will be represented.

Finally, the main weighed criteria with the AHP method will be used to classify the appropriate area and determine the best area for the wind farm.

5.1. Restrictions

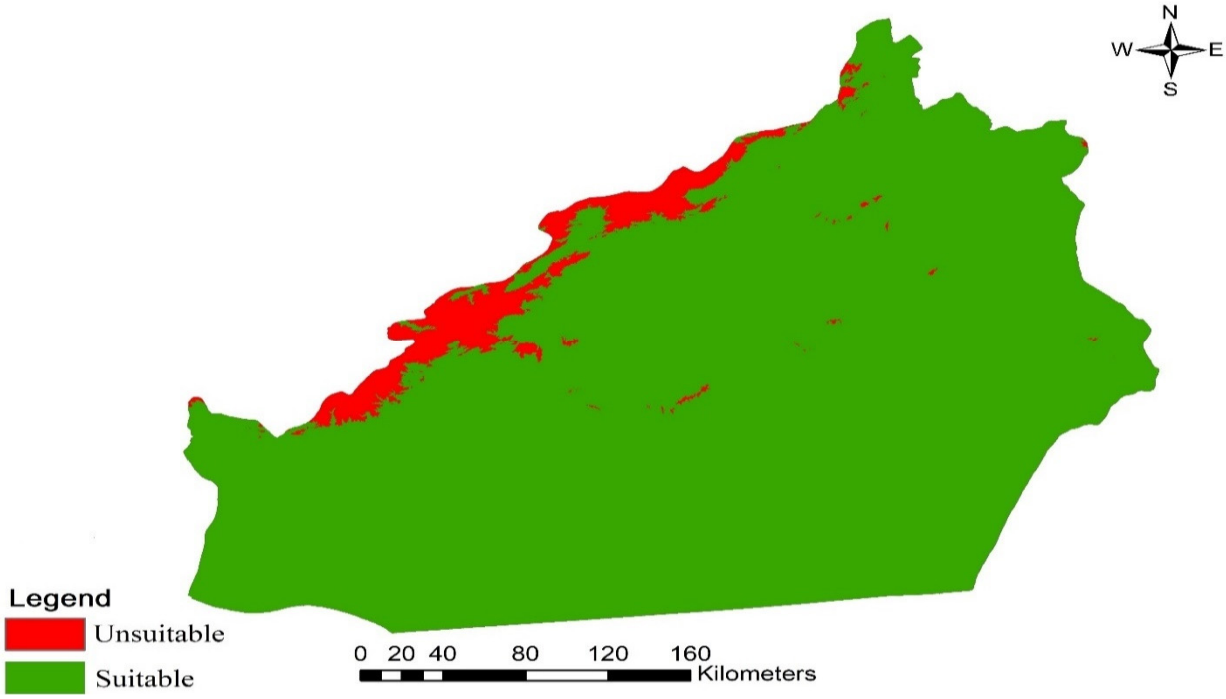
Topological, ecological, and structural restrictions were specified based on the local and constitutional rules and regulations and recent studies. Sloping and high lands were less considered due to problems in installing turbines, complex and costly repairs, and the maintenance of turbines. Proximity to faults was also avoided due to the dangers it may cause the structures. To ensure security and minimize the problems of turbines for the general public, the permitted distance of turbines from communication routes, fuel, and energy transmission lines, and airports must also be observed. One of the disadvantages of wind turbines is the environmental hazards in the habitats of various animals, particularly birds. Therefore, environmental considerations keep the turbines far from the protected areas and rivers. By applying these restrictions, unsuitable areas for wind farm construction will be identified. These areas will be shown in red on the map and will be removed from the final desired map, which will be investigated by applying the criteria.

5.1.1. Topological Restrictions

The topological restrictions are represented in Table 8. The digital elevation model was used to create a slope map of the province. According to the references mentioned in Table 8, unsuitable areas with an altitude of more than 2000 m and slopes of more than 30% were considered. A distance of fewer than 500 m from the faults was also considered unsuitable. Figure 8 shows the suitable and unsuitable areas based on the topological restrictions mentioned in Table 8. The red areas indicate inappropriate locations, and the green areas indicate appropriate areas.

Table 8. Topological restrictions.

Sub-Criteria	Buffer Zones	References
Elevation (m)	>2000	[6,72]
Slope (percent)	>30	[73]
Faults (m)	<500	[6]



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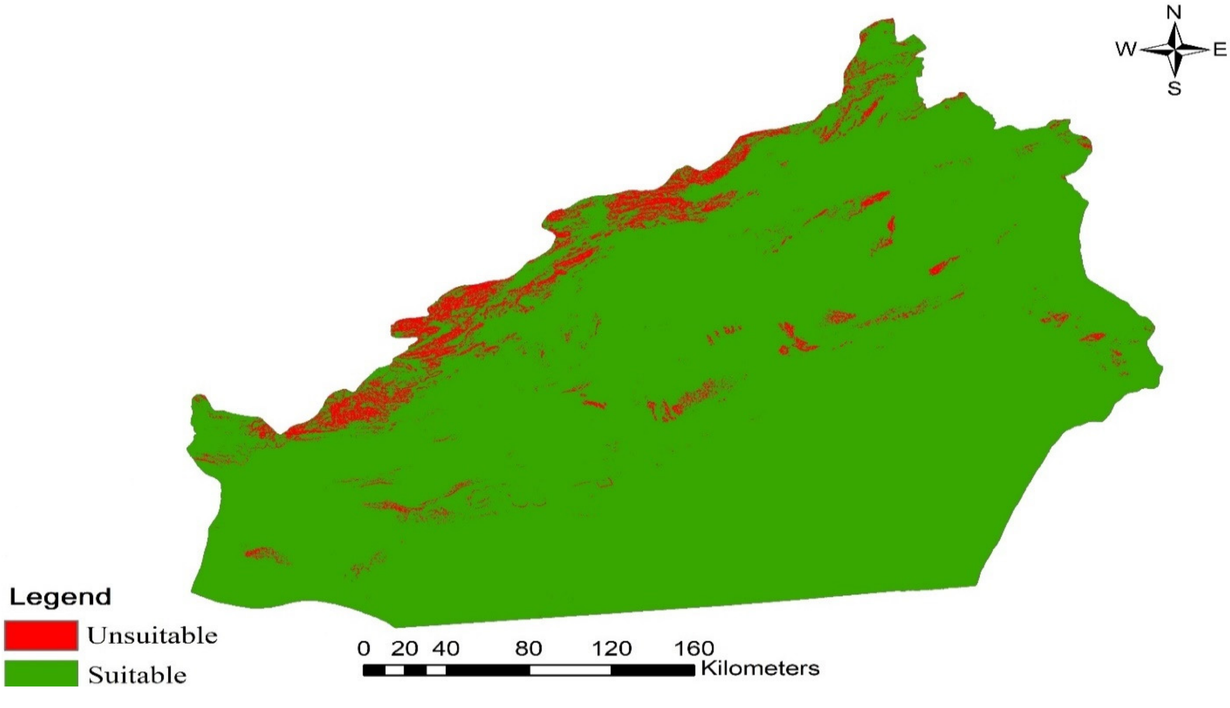
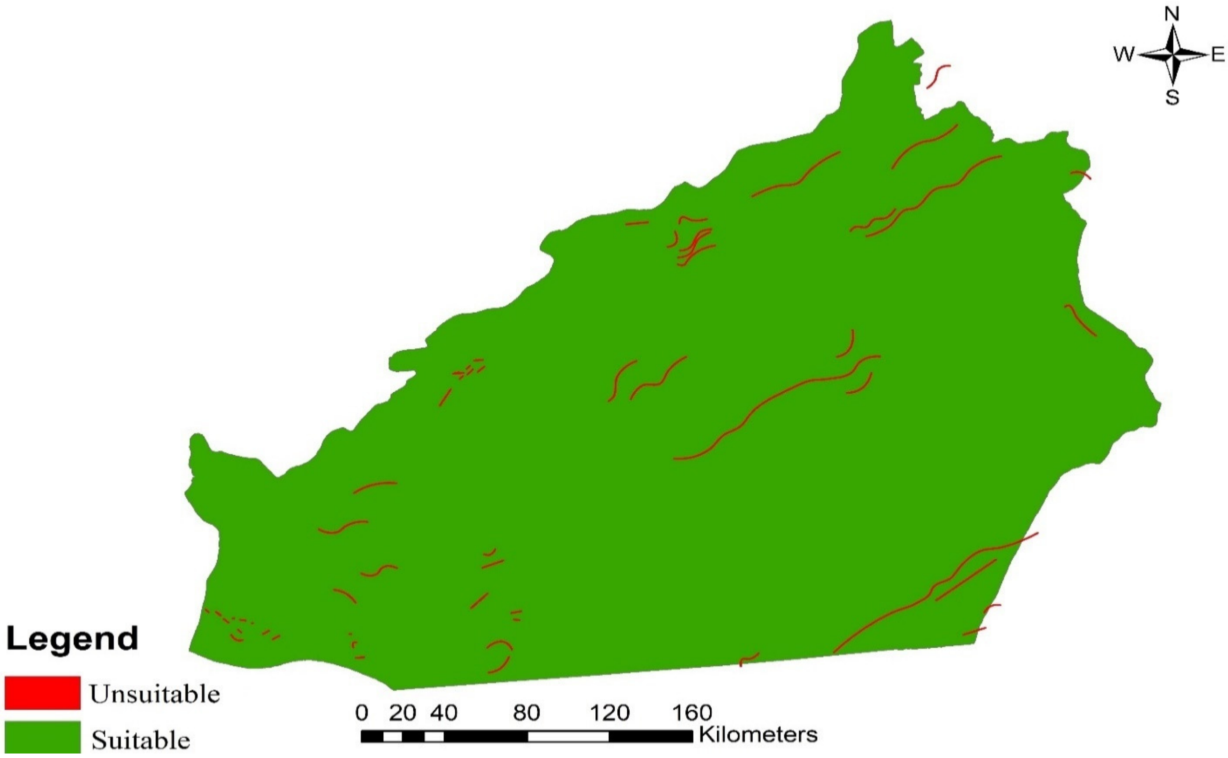


(**b**)

Figure 8. *Cont*.



(c)

Figure 8. Topological restrictions (**a**) elevation map. (**b**) slope map. (**c**) faults buffer zone.

5.1.2. Structural Restrictions

The structural restrictions are given in Table 9. According to the latest maps prepared in the planning studies of the Semnan province, carried out by the Planning and Budget Organization of the Ministry of Interior in 2016, the location of roads, oil and gas transmission lines, high voltage power lines, substations, railways, and the airports were identified [74]. The buffer areas are specified based on the mentioned references in Table 9.

Table 9. Structural restrictions.

Sub-Criteria	Buffer Zones	References
Highways and roads (m)	<500	[6]
Oil and gas transmission lines (m)	<500	[6,72]
High voltage power lines (m)	<250	[6,72,75]
Substations (m)	<250	[72]
Railways (m)	<300	[6]
Airports (m)	<2500	[6]

Figure 9 illustrates the suitable and unsuitable structural areas according to the buffer zones of Table 9. The red areas are unsuitable buffer zones, and the green areas are suitable according to structural restrictions. The area of Semnan province is equal to 97,491 km^2. Based on the calculations made according to Table 9, 3864.2 km^2 (3.96%) of the province's total area is among the unsuitable areas.

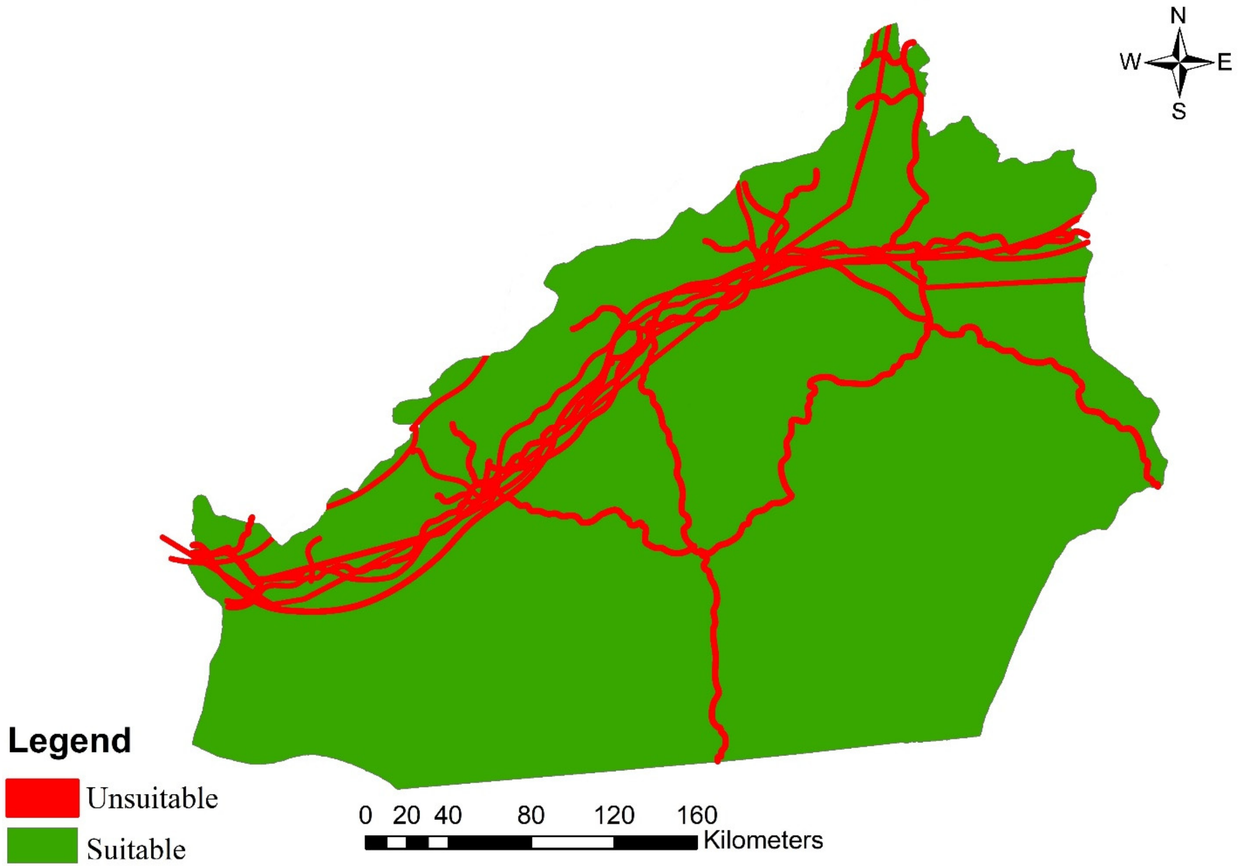


Figure 9. Suitable and unsuitable areas according to structural restrictions.

5.1.3. Ecological Restrictions

Table 10 shows the ecological restrictions. Given the planning studies of the Semnan province [74], the location of environmental protected areas, urban and rural areas, and water bodies and rivers were identified, and buffer zones were specified according to the mentioned references in Table 10.

Table 10. Ecological restrictions.

Sub-Criteria	Buffer Zones	References
Environmental protected areas (m)	<2000	[6]
Urban areas (m)	<2500	[76]
Water bodies (m)	<1000	[6]
Rivers (m)	<500	[6]

Figure 10 exhibits the suitable and unsuitable ecological areas according to the buffer zones of Table 10. According to the ecological restrictions, the red and green areas are unsuitable and suitable zones. Based on the calculations made according to Table 10, 18,052.24 km^2 (18.51%) of the province's total area is among the unsuitable areas.

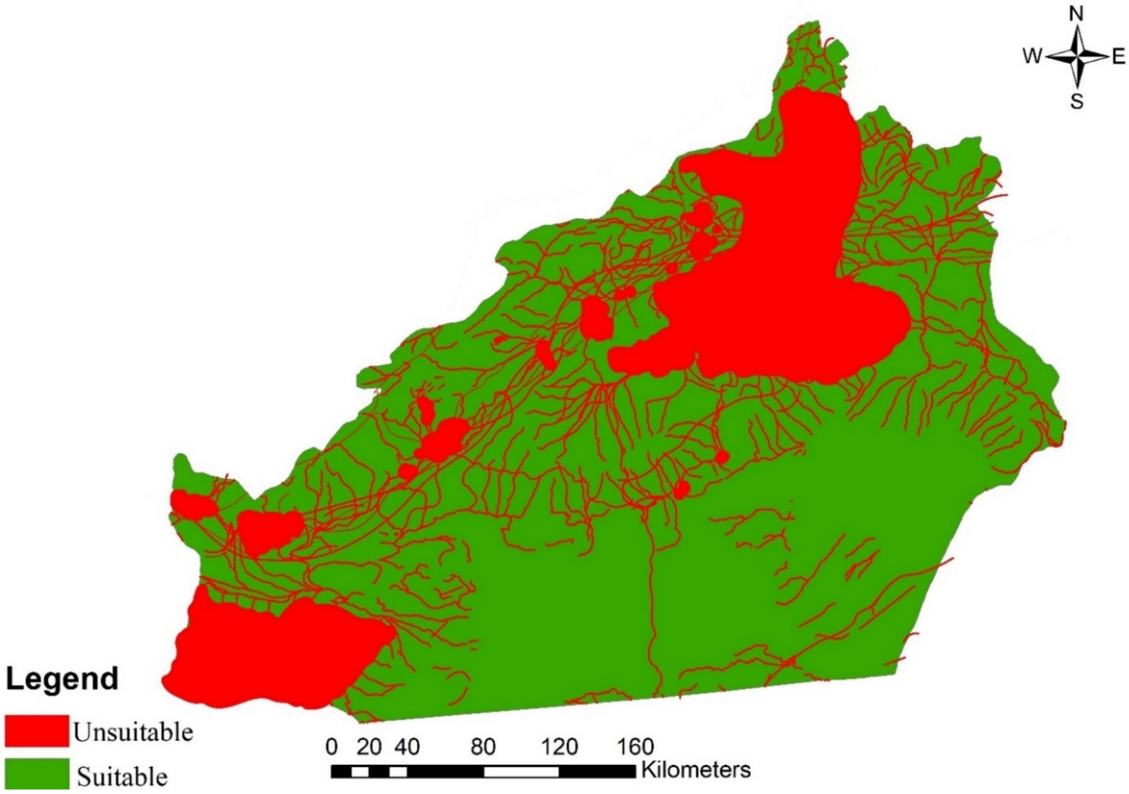


Figure 10. Suitable and unsuitable areas according to ecological restrictions.

Figure 11 shows Semnan province by applying all the restrictions and buffer areas. The areas marked in red and green are unsuitable and suitable, respectively. The total unsuitable areas are equal to 35,094.042329 km^2, which is 36.2% of the total province area.

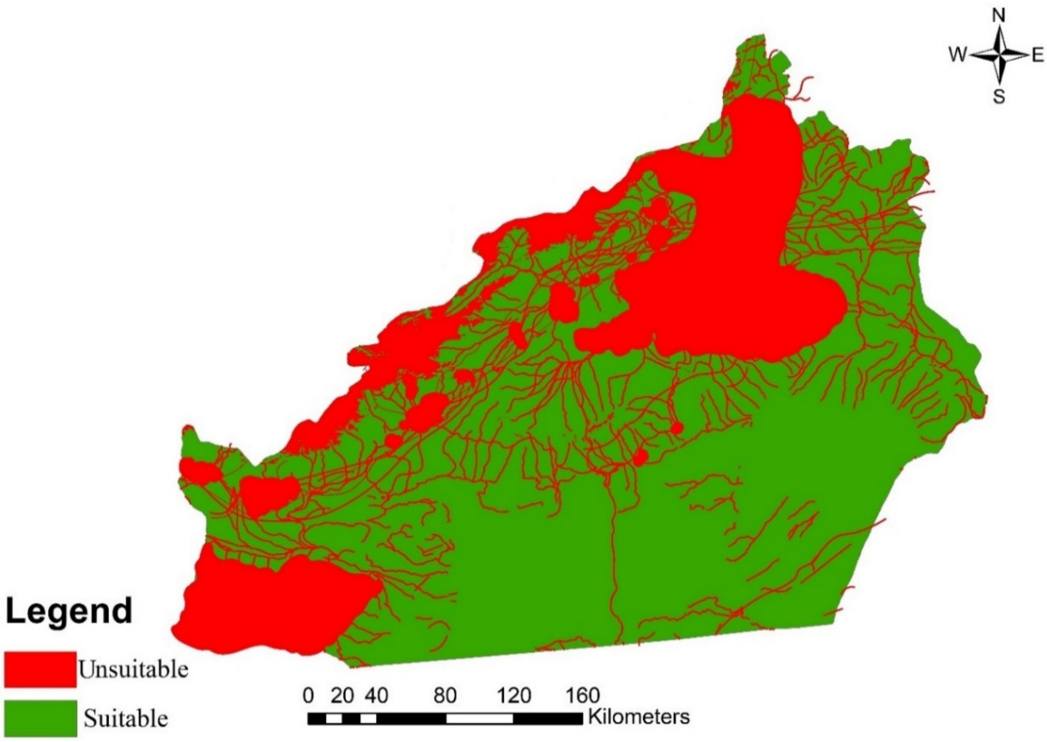


Figure 11. All buffer areas of Semnan province.

5.2. Executing AHP Weights

In almost all studies, the most crucial criterion for solving wind farms' site selection problems is always the region's wind potential [76–80], which also can be seen in calculating the weights of the criteria in the current work. Higher wind speeds in the area mean that it is possible to use larger turbines.

Data from the Renewable Energy and Energy Efficiency Organization (SATBA) were used to prepare the wind map of the province. For this purpose, the wind data of 13 stations in and around the province were employed. Appendix A (Table A2) shows the entire data of SATBA for the 13 stations. Moreover, Table 11 reveals the speed data for the 13 stations. A wind map of the whole province was prepared through interpolation techniques, portrayed in Figure 12. The wind map was reclassified into nine classes. The areas with the highest wind speed were given the highest score, and those with the lowest wind speed were given the lowest score. The minimum and maximum wind speeds were between 3.6 and 5.3 m/s. Moreover, the central areas of the province, which are generally uninhabited and include desert and flat lands, have the best wind speeds.

Table 11. Wind speed data of SATBA stations.

Row	Station	Latitude (Deg)	Longitude (Deg)	Average Wind Speed (m/s)
1	Qom	50.88	34.64	4.92
2	Vesf	50.94	34.19	4.92
3	Friruzhuh	52.77	35.75	4.33
4	Aqqala	54.45	37.01	3.6
5	Marave tappe	55.95	37.9	3.83
6	Bojnurd	57.33	37.47	5.25
7	Davaran	56.88	36.44	3.71
8	Rudab	57.31	36.03	5.21
9	Afriz	59	33.45	4.7
10	Kahak	53.32	35.14	4.21
11	Moalleman	54.56	35.21	5.3
12	Hadadeh	54.73	36.26	4.95
13	Semnan	53.39	35.58	3.64

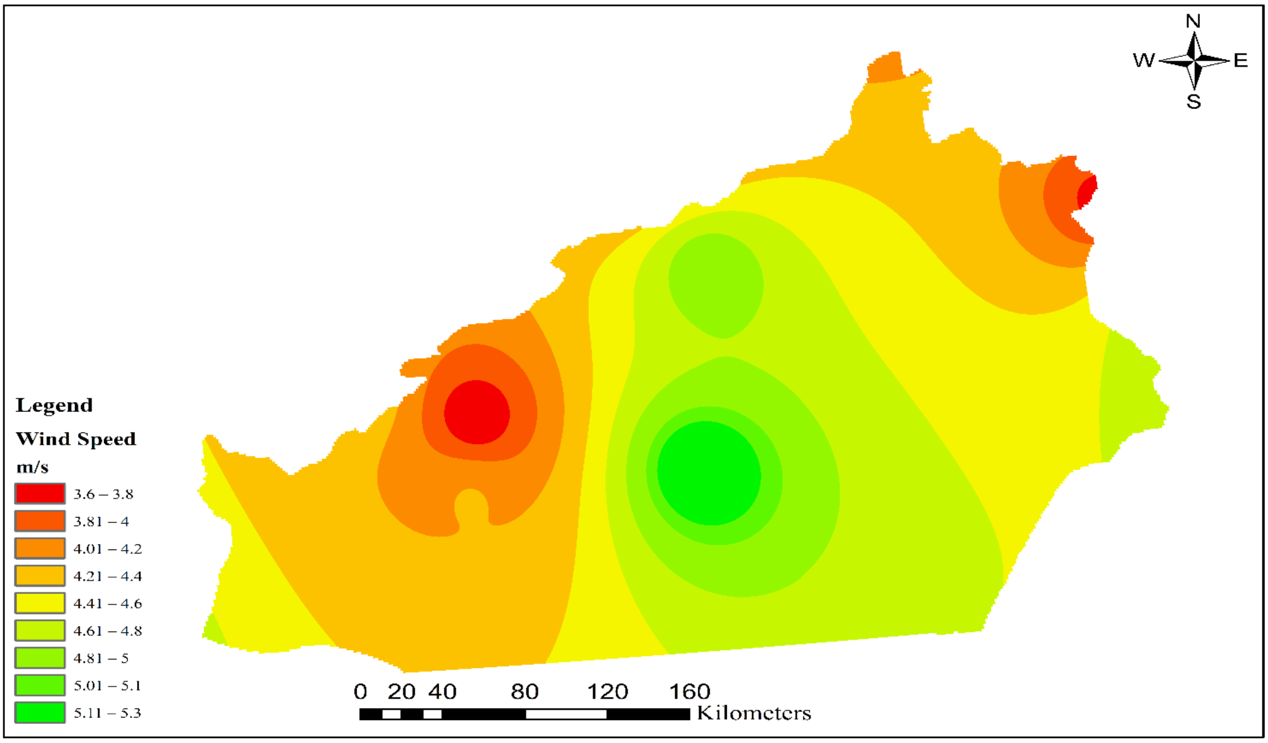
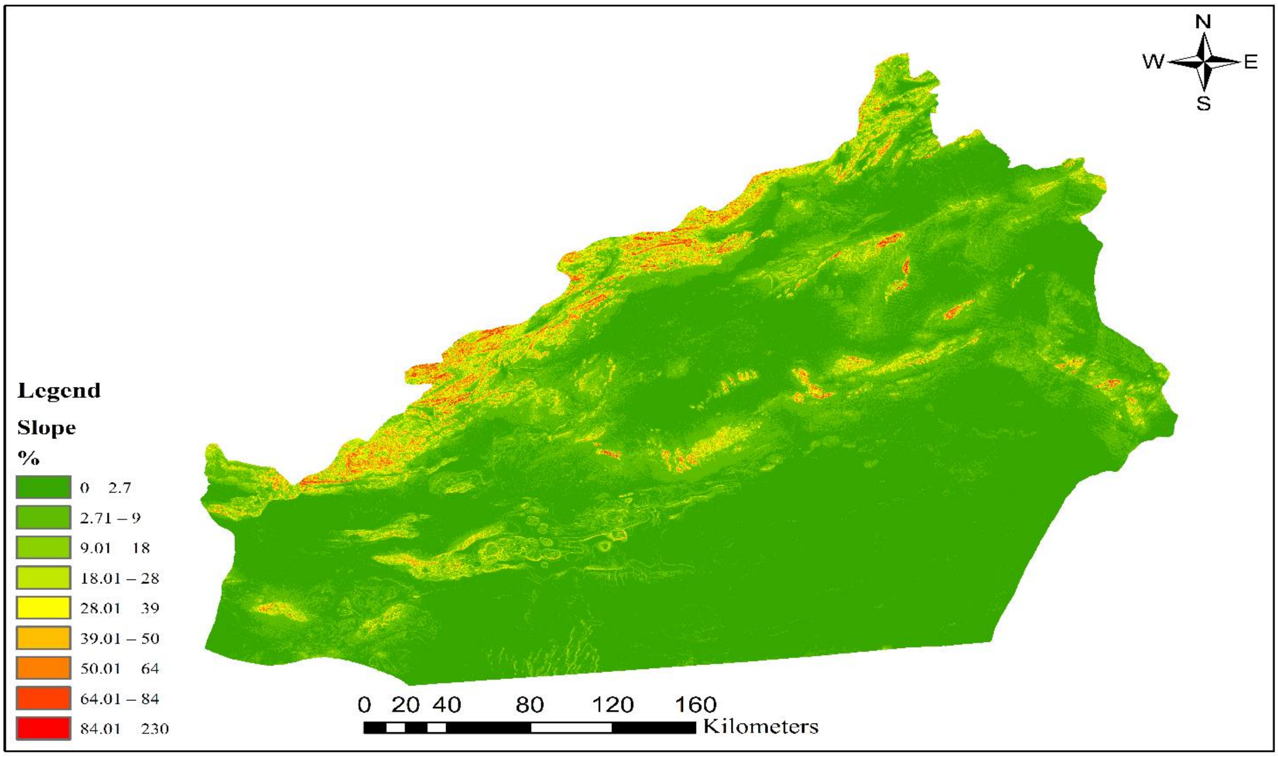
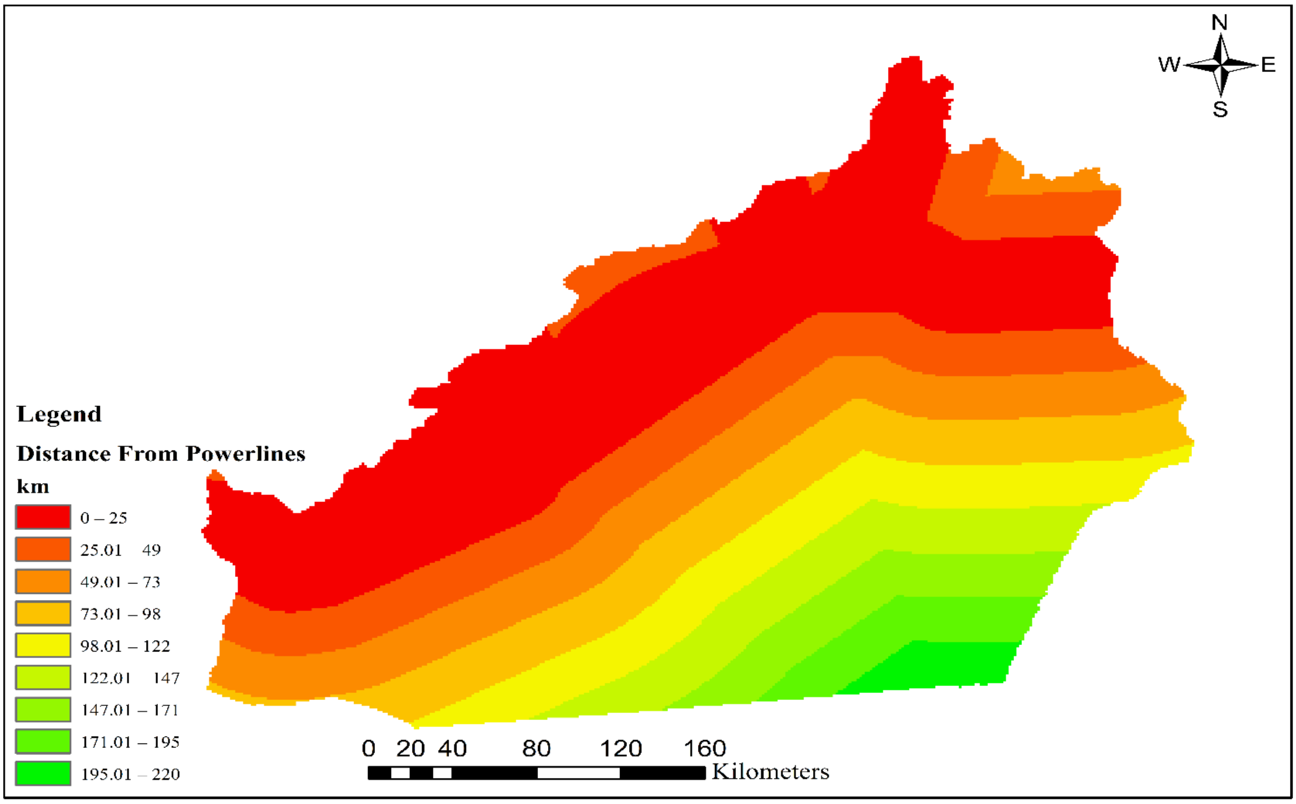


Figure 12. Wind map of Semnan province (m/s).

The rest of the criteria were classified according to the pairwise comparison, and the weights were specified with the AHP method. The classified maps are represented in Figure 13. Each map is categorized into nine classes.

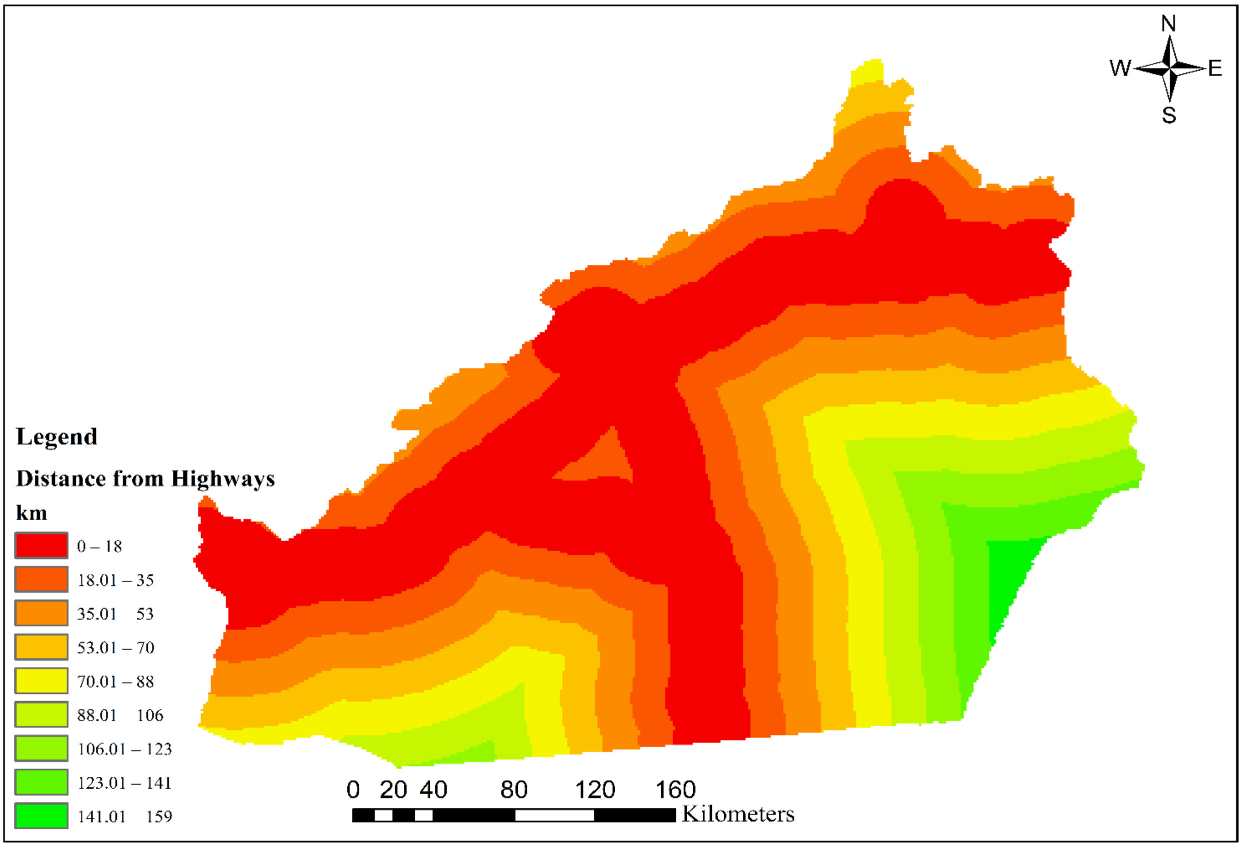


(**a**)

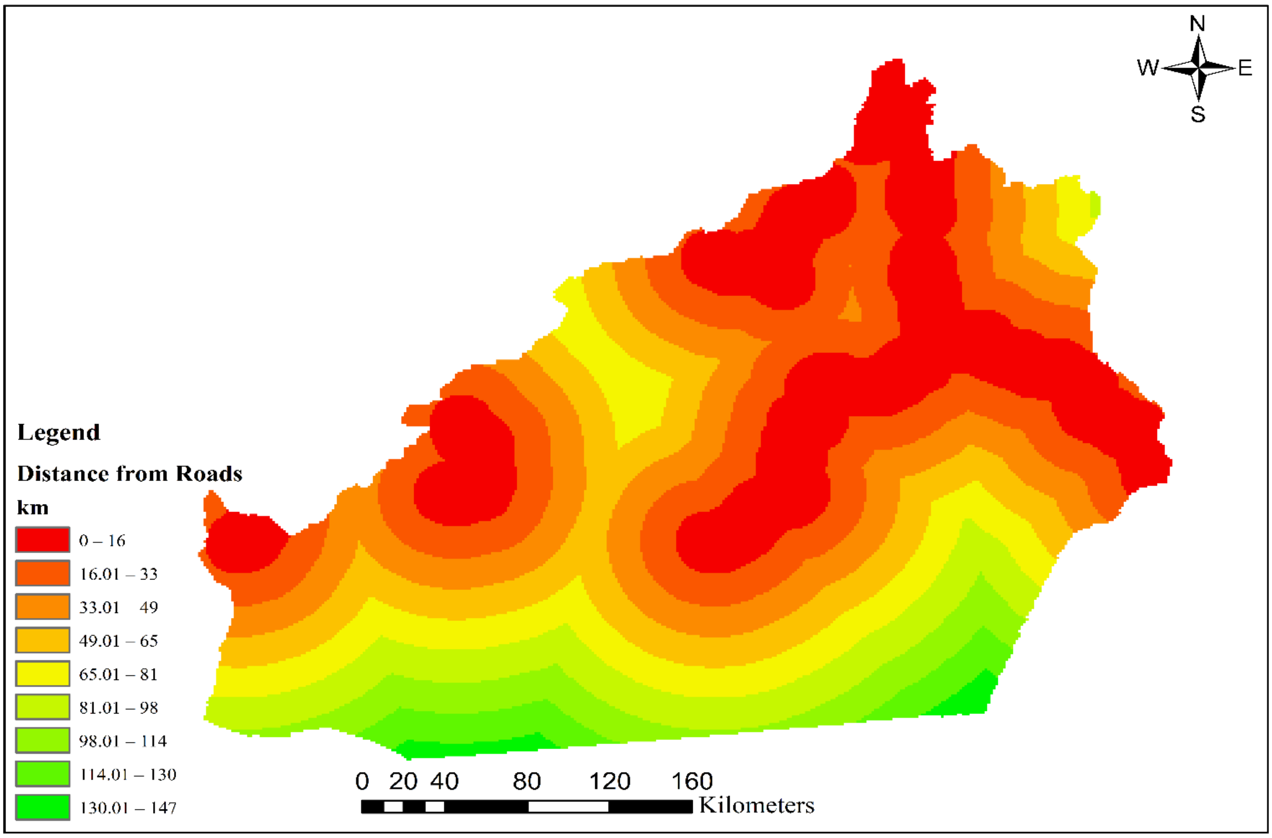


(**b**)

Figure 13. *Cont.*

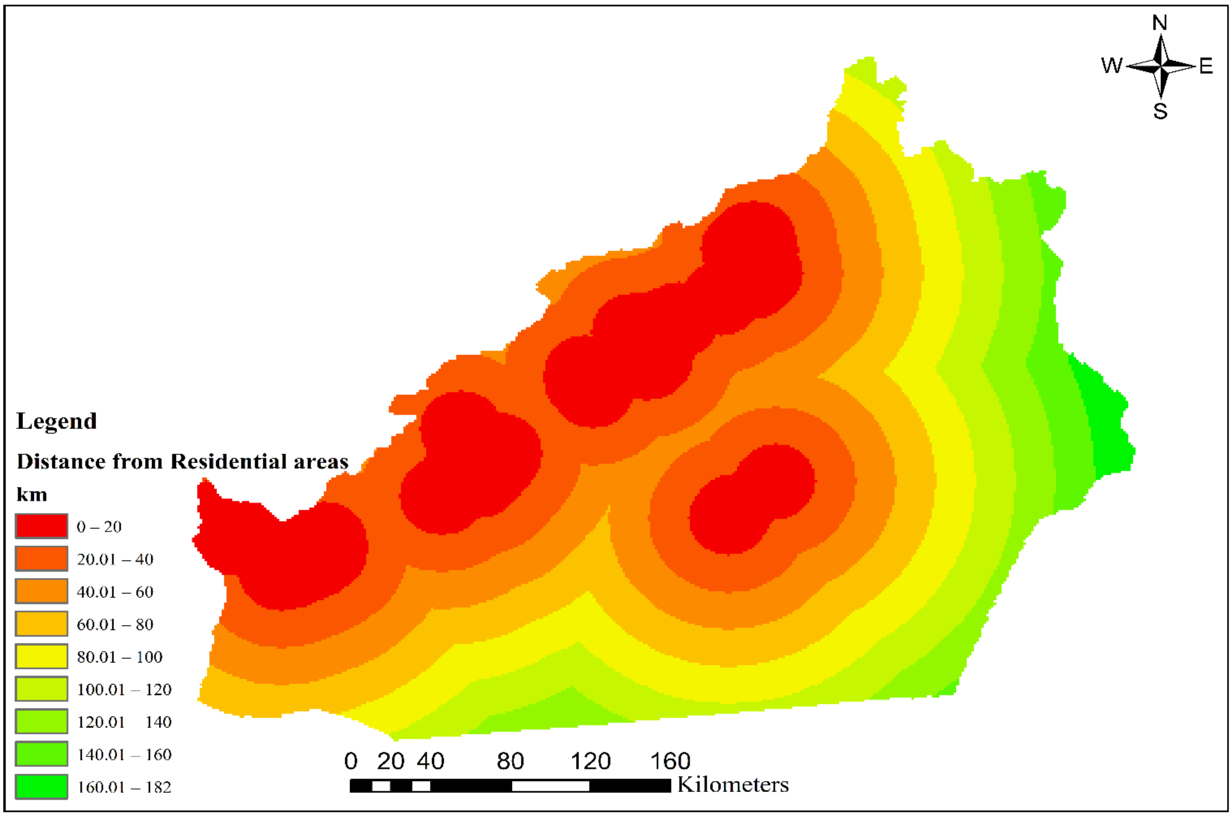


(c)

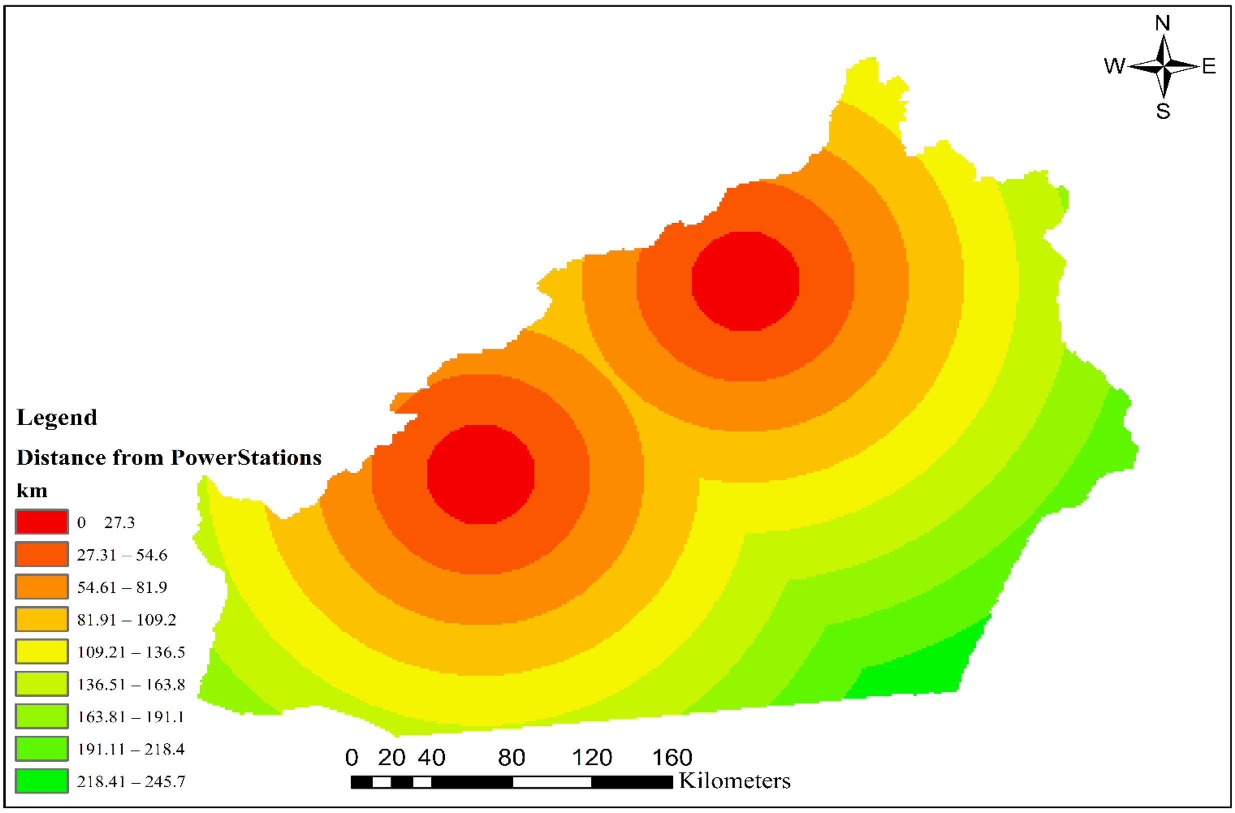


(d)

Figure 13. *Cont.*



(**e**)



(**f**)

Figure 13. Classified map of the province based on different criteria (**a**) Slope map. (**b**) Distance from powerlines. Distance from (**c**) highways and (**d**) roads. (**e**) Distance from the residential area. (**f**) Distance from power stations).

A slope map was prepared via a digital elevation model (DEM). It was then reclassified, and each class was rated. On account of the importance of the low slope area, these areas were given a higher score.

The distance from other features, such as residential areas, power lines, power stations, and highways and roads, was also classified into nine categories. The areas closer to communication roads and stations and power lines are more important. Therefore, the shortest distance was given the highest score and the farthest distance the lowest score.

6. Results and Discussions

In this section, the results will be displayed. The regional data and the method shown in Figure 7 were applied to show the map's layers, constraints, and classifications. Furthermore, the results of similar studies are mentioned and compared, and the wind energy in the province is compared with other provinces.

After executing the AHP weights for the criteria, the classified map is illustrated in Figure 14. The province was categorized into nine classes, and the green and red areas, respectively, are the best and worst areas for this province. No restrictions were applied in this figure. Looking more carefully at restrictions and comparing them with the slope and elevation map, it can be seen that many of the green areas that are prone to wind farm construction are located in places with high altitudes and high slopes.

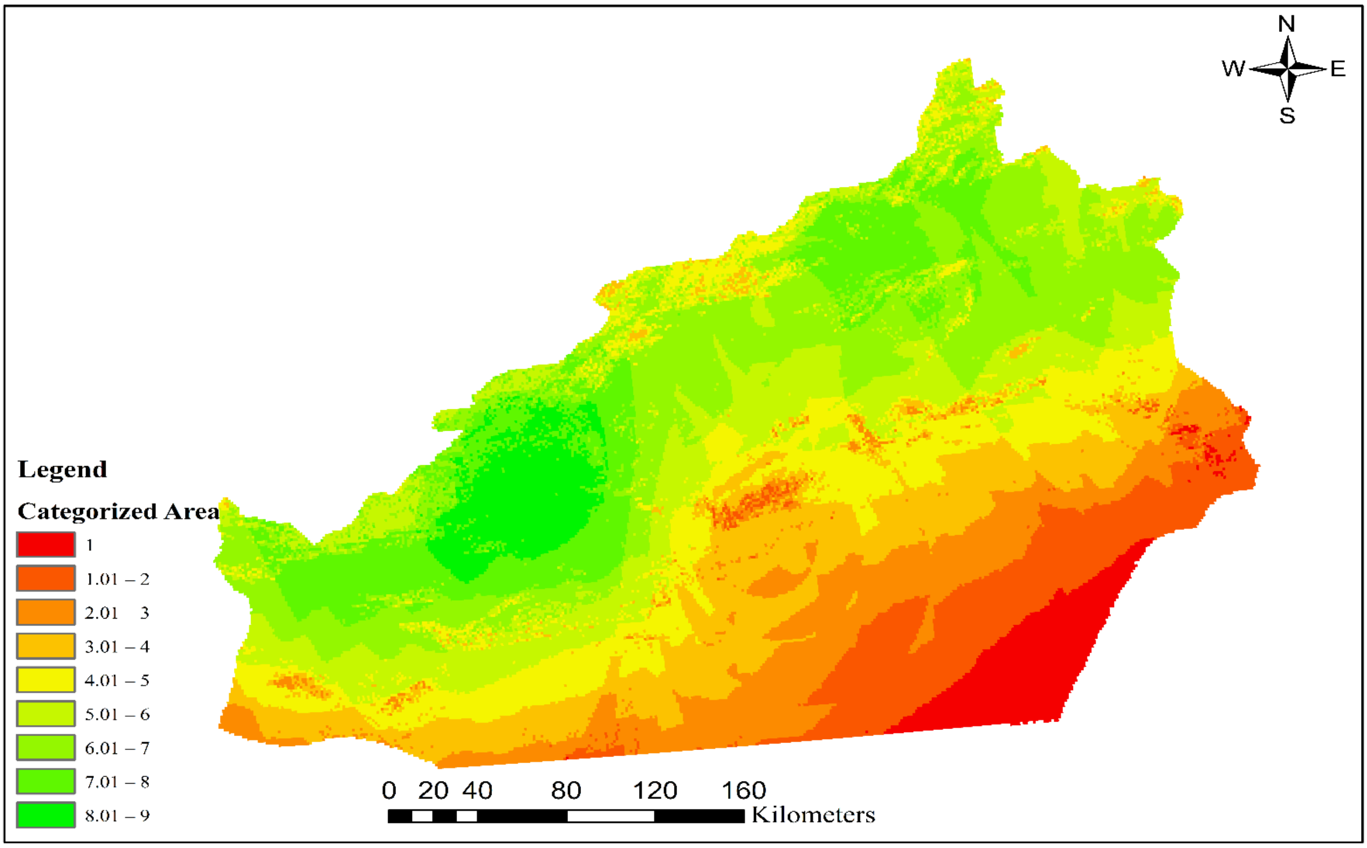


Figure 14. Categorized area based on AHP criteria.

The other essential criteria for this site selection study were the distance from communication routes, substations, and power lines. The remoteness of communication routes, substations, and power lines have adverse effects due to the increase in the cost of installation and maintenance costs. Moreover, the construction of new substations and power transmission lines will cause a sharp increase in the initial and maintenance costs of the whole system. In addition, the increment in the power line's lengths causes more power loss and voltage drop. Therefore, more distant lands have become less of a priority.

The importance of these criteria is of great significance. It has made the northeastern regions of the province, with lower wind speed than the center of the province, have a higher priority for the construction of wind farms. Consequently, the southern regions have the worst conditions due to being deserted and far distance from the roads and power network facilities.

Restrictions were applied to reach the final classified area. The red areas shown in Figure 11 have been removed from the final map based on existing restrictions. Figure 15 shows the final classified map after the restrictions are applied. Due to many residential areas, communication roads, and electricity installations in the northern part of the province, these buffer zones were removed from the final map.

After removing the restricted areas, the best available areas are located on the western side inclined to the province's center and in a small part in the east of the province. According to the classified map, southern areas that are not restricted on account of low population density and lack of cities and protected areas have less priority.

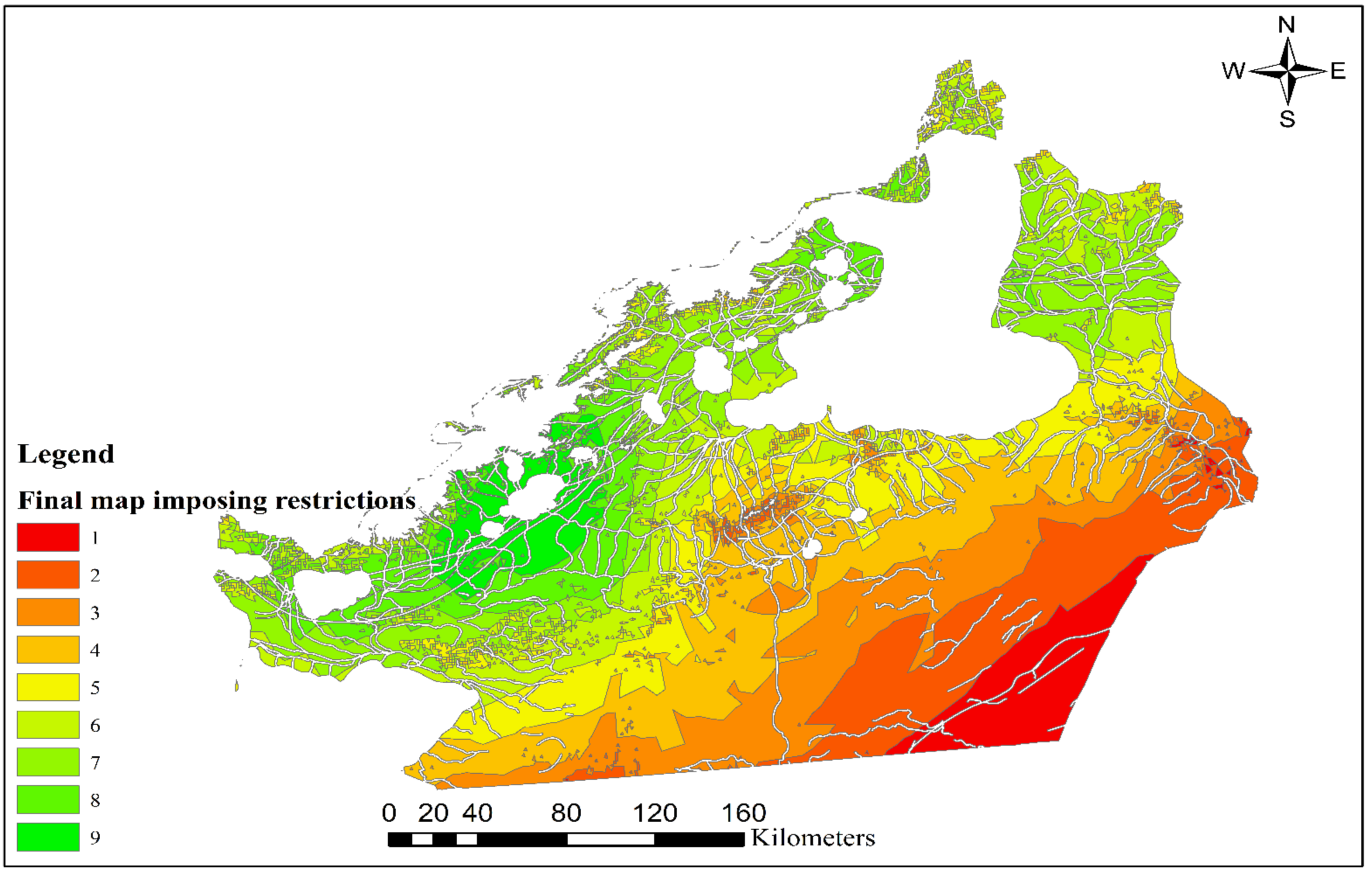
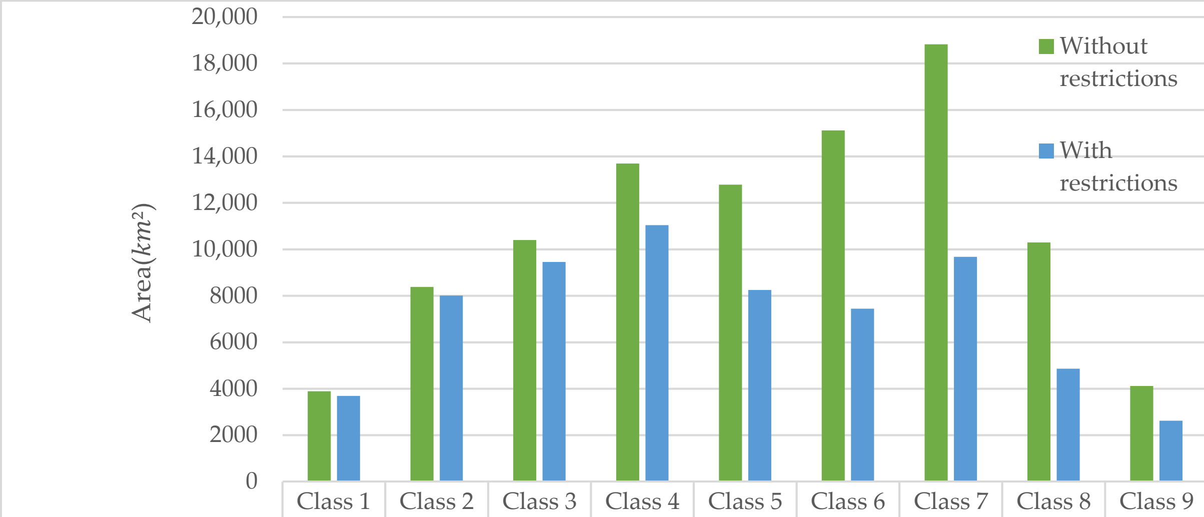


Figure 15. Final categorized map by imposing restrictions.

Figure 16 demonstrates the area of each class with and without restrictions. Classes 9 to 1 are, respectively, the best and worst areas. Class 4 has the largest area (about 16.9%), followed by Class 3 with 14.5%. Only slightly more than 4% of the areas are in Class 9, the best class. The total of the classified areas after removing the buffer zones is a little over 65,000 km^2.



Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9
Without restrictions	3885.812	8382.79	10,401.50	13,689.79	12,780.36	15,113.98	18,822.11	10,295.18	4119.402
With restrictions	3687.18	8005.64	9451.82	11,036.85	8248.59	7446.42	9672.088	4857.045	2618.55

Figure 16. Area of each Class with and without restricted area.

Comparison with Similar Studies

Herein, the wind potential in Semnan province was investigated according to specific criteria. Owing to the increasing popularity of renewable energy, a large number of such articles are placed in various scientific databases annually. However, no similar articles examined Semnan province regarding wind energy potential among the published articles.

In 2011, Mir Hosseini et al. [81] Investigated wind potentials in five locations in Semnan province. Their only criterion to measure wind energy potential was wind speed. To this end, wind data were examined in 3-h intervals between 2003 and 2007. Finally, by comparing wind data, it was concluded that the north area of Damghan has the best conditions among the evaluated areas. The wind was the most important criterion for measuring areas in this paper. According to Figures 2 and 16, the Semnan area can be found among the classified areas, according to which, Damghan is located in the area with grades 7–9, showing good conditions in terms of wind potential.

Moreover, various studies have been conducted to investigate the wind farm potential in the other provinces of Iran. Barzehkar et al. investigated the wind and photovoltaic site potential in Isfahan province, which locates in the south of Semnan. They used a weighted linear combination, AHP, GIS, and fuzzy logic to evaluate the province's area. Their AHP results indicated wind speed and distance from power lines as the most important criteria. According to their final results, almost 15% of the total area had the most potential for wind farm sites, which are mainly located in the province's northeast [82].

Nadizade et al. investigated the multi-renewable energy farms in four eastern provinces of Iran. Three of these provinces locates in the east of Semnan and have a border with this province. According to fuzzy logic and ANP wights, wind speed, distance from urban and protected areas, distance from roads, slope, and elevation were the essential criteria for the wind farm site. Based on their final results, almost 8% of the total study area had a high potential for the wind farm, mostly located in the south part of the study area [83].

In another study, GIS and AHP were used to investigate the wind farm and hydrogen production potential in Yazd, one of Iran's central provinces. According to the AHP weights, the economic criteria such as distance from an urban area and power lines were more important than technical criteria, including slope and wind speed, which is a significant difference between this study and other mentioned studies. Furthermore, they showed that the central and north parts of the study area have the highest potential for extracting wind energy and hydrogen production [84].

Comparing the results of the weighting methods of this study and other mentioned studies show that in most of the studies, wind speed is the essential criterion. Although, there is no similar study to be compared with the present study results in Semnan. Other studies with similar methods in other provinces show that the central and eastern part of Iran has a good potential for wind farm sites. Putting together the results of the study in different areas can provide an overview of wind potential in the whole country. Furthermore, comparing the criteria and restrictions in various regions can give an overview of the general restrictions and criteria in the country.

7. Conclusions

This study investigated an MCDM system for wind farm site selection in Semnan, Iran. The SATBA meteorological station data were employed to classify the area in terms of wind speed. Topological, ecological, and structural restrictions were specified based on the local and constitutional rules and regulations. These restrictions divided the province area into two suitable and unsuitable areas. According to the opinion of the experts, seven main criteria were selected and pairwise compared. The parameters such as distance from power stations, power lines, and distance from communication routes are included in the main criteria to consider the economic factors. Afterward, an AHP method was applied to categorize the suitable area into nine classes to represent the wind farm potential in various province locations. The results show that an MCDM based on AHP is useful for splitting a complicated problem into smaller parts and solving them effectively and does not need a genuine dataset.

This study shows that the most favorable areas of the province to extract wind energy can be used for practical goals. According to the results, almost 36.2% of the total study area is restricted due to being adjacent to environmentally restricted areas, populated areas, and communication routes. Most of the best areas with the highest wind farm potential are located in the northern part of the province. Although these areas have a lower wind speed, the lower distance to the electrical facilities and communication routes could reduce the initial and maintenance costs and make the project more justifiable. The final categorized map shows that the Aradan and Sorkhe regions, located in the province's northwest part, have the highest potential for wind farms. In contrast, the south and southeast region, which mainly consists of desert lands and unurbanized areas, has the least wind farm potential due to the greater distance from communication routes and power grid facilities. The final map is categorized into nine classes. The results represent almost 17.5% of the total study area placed in the three classes with the highest wind farm potential. At the same time, about 21.68% of the study area locates in the three classes with the slightest wind farm potential.

Other renewable resources, including solar energy, offshore wind farms, and geothermal plants, depend on ecological, economic, and environmental factors. In future papers, the MCDM systems could facilitate the site-selection problems for other renewable resources. Additionally, various methods, including fuzzy AHP, Entropy, Dematel, and Swara, can be used in site-selection problems and the results can be compared.

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Informed Consent Statement: This Study Do not involve any human.

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Appendix A

Table A1. Academic information of the experts who participated in the decision-making process and pairwise comparison of criteria.

Row	Number of Participants	Academic Degree	Organization	Field of Expertise or Related Job
1	4	University professor	Tehran University, Tehran, Iran	Energy and environment, Renewable energies
2	2	University professor	Shahid Beheshti University, Tehran, Iran	Civil engineering, Water and environmental science, Renewable energies
3	4	Industrial technician	-	Wind farm site engineers
4	10	University student (Master and PHD)	Tehran University, Tehran, Iran	Renewable energies engineering

Table A2. Data of SATBA stations for 13 stations inside and around the Semnan.

Row	Latitude (Deg)	Longitude (Deg)	Average Wind Speed (m/s)	Wind Direction (Deg)	Solar Radiation (W/m^2)	Station	Province
1	50.88	34.64	4.92	208.14	117.35	Qom	Qom
2	50.94	34.19	4.92	208.14	117.35	Vesf	Qom
3	52.77	35.75	4.33	196.32	-	Friruzhuh	Tehran
4	54.45	37.01	3.6	185.58	178.04	Aqqala	Golestan
5	55.95	37.9	3.83	186.71	179.51	Marave tappe	Golestan
6	57.33	37.47	5.25	172.32	197.39	Bojnurd	North Khorasan
7	56.88	36.44	3.71	181.19	213.06	Davaran	Isfahan
8	57.31	36.03	5.21	131.67	203.89	Rudab	Razavi Khorasan
9	59	33.45	4.7	147.6	238.1	Afriz	South Khorasan
10	53.32	35.14	4.21	152.8	176.25	Kahak	Qom
11	54.56	35.21	5.3	181.84	222.54	Moalleman	Semnan
12	54.73	36.26	4.95	161.45	214.24	Hadadeh	Semnan
13	53.39	35.58	3.64	199.8	181.96	Semnan	Semnan

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