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Locating wind farm for power and hydrogen production based on Geographic information system and multi-criteria decision making method: An application

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HIGHLIGHTS

- The suitable place to produce hydrogen by wind energy is identified in Yazd province.
- The Geographic information system method was used to eliminate inappropriate areas.
- The Analytic Hierarchy Process (AHP) method was used to weight the criteria.
- The GIS-AHP methods were a powerful tool for identifying places to produce hydrogen.

ARTICLE INFO

Article history:
Received 10 July 2021
Received in revised form
20 January 2022
Accepted 9 March 2022
Available online 31 March 2022

Keywords:
Geographic information system
Yazd province
Hydrogen production
Wind energy
Multi-criteria decision making methods

ABSTRACT

Hydrogen generation from renewable energy resources is considered as a suitable solution to solve the problems related to the energy sector and the reduction of greenhouse gases. The aim of this study is to provide an integrated framework for identifying suitable areas for the construction of wind farms to produce hydrogen. For this purpose, a combined method of Geographic Information System (GIS) and multi-criteria decision making (MCDM) has been used to locate the power plant in Yazd province. The GIS method in the present study consisted of two parts: constraints and criteria. The constraint section included areas that were unsuitable for the construction of wind farms to produce power and hydrogen. In the present study, various aspects such as physical, economic and environmental had been considered as constraints. In the criteria section, eight different criteria from technical aspects (including average wind speed, hydrogen production potential, land slope) and economic aspects (including distance to electricity grid, distance to urban areas, distance to road, distance to railway and distance to centers of High hydrogen consumption) had been investigated. The MCDM tool had been used to weigh the criteria and identify suitable areas. Analytic Hierarchy Process (AHP) technique was used for weighting the criteria. The results of AHP weighting method showed that economic criteria had the highest importance with a value of 0.681. The most significant sub-criterion was the distance to urban areas and the least significant sub-criterion was the distance to power transmission lines. The results of GIS-MCDM analysis had shown that the most proper areas were in the southern and central sectors of Yazd province. In addition, the

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https://doi.org/10.1016/j.ijhydene.2022.03.083

feasibility of hydrogen production from wind energy had shown that this province had the capacity to generate hydrogen at the rate of 53.6–128.6 tons per year.

Introduction

In recent decades, providing sustainable energy sources for human societies were one of the biggest challenges [1]. Global energy demand was expected to increase by an average of 8% per year between 2000 and 2030 [2]. Fossil fuels were generally the primary energy source for all societies; according to the International Energy Agency (IEA), fossil fuels fulfilled 80% of global energy demand and were accounting for 90% of greenhouse gas emissions [3]. Rising environmental concerns, declining fossil fuel resources, and high prices of electricity generation have led to the rapid use of renewable energy sources and the transition to clean energy carriers such as hydrogen fuel [4,5].

Wind energy is one of the most sustainable and reliable forms of renewable energy [6]. Wind is currently growing as a sustainable, environmentally friendly and economically viable source of energy [7]. The importance of wind energy has increased in recent years due to the use of various incentive policies in countries to build wind farms [8]. The progression of wind energy conversion technology has led to the competitive price of energy production from the wind source with price of energy production from fossil fuels [9]. Therefore, wind is a harmless form of energy that can be cost-effective, sustainable, and environmentally safe and can play a significant role in reducing CO_2, SO_x and NO_x [10].

There has been a lot of research which has argued for hydrogen as an oncoming role to the problems of energy storage, positive environmental effects and new energy sources for transportation. Many hydrogen-fueled automobile projects had started in recent years around the world driven by hydrogen fuel [11,12]. In addition, the hydrogen vehicle landscape states that at least 400 million cars will be hydrogen-powered by 2050 [13]. In general, hydrogen fuel is also used indirectly in many industries, as shown in Fig. 1.

There are standard techniques for generating hydrogen from water such as electrolysis, photocatalytic water separation, radiolysis, thermolysis, etc. [15]. The utilization of renewable energy sources to generate hydrogen by electrolysis of water offers the advantage of lowering pollution in the environment [16].

There have been many studies in the literature that have focused on the feasibility of producing hydrogen from wind resource. Genç et al. [17] evaluated wind resource for hydrogen production in the central region of Antalya in Turkey. They studied five various areas in Turkey and reported that the maximum hydrogen production at the Pinarbasi station was 6.3 tons per year. Iqbal et al. [18] evaluated capacity of wind resource for hydrogen generation in Sindh province in Pakistan. They studied eight different stations and the highest amount of hydrogen production was found in Nooriabad station. Rodríguez et al. [19] evaluated hydrogen generation from wind resource in Cordoba, Argentina. The results showed that hydrogen production from the electrolyzer unit could be used as fuel in automobiles in the area and was economically competitive with fossil fuels. Aiche-Hamane et al. [20] evaluated the viability study for hydrogen generation from wind resource in the Ghardaia. They reported that the region had the potential to produce 4200 Nm^3 of hydrogen. In Iran, Alavi et al. [21] investigated the generation of hydrogen from wind resource in Sistan and Baluchestan province. They used wind speed data in five different places and the highest rate of hydrogen generation per year was related to Lutek station with 39.8 tons per year. Mostafaeipour et al. [22] evaluated the viability of hydrogen generation from a wind resource in Fars province. They reported that hydrogen production in the city of Abadeh in Fars province could be the potential to supply fuel for 22 cars per week.

Mentioned studies had only reported the potential for hydrogen production from the wind source and had not identified suitable locations for the installation of integrated hydrogen generation systems from wind turbines. Considering that the installation of renewable energy power plants, specifically the expansion of wind farms, requires a high investment, so the choice of suitable places is an important step in improving efficiency and reducing the risk of investment [23,24]. The high investment, which includes not only the cost of the turbine, but also the cost of maintenance, transmission lines, land use etc., leads the price of wind energy relatively high compared to the price of electricity generation by fossil fuel [25]. To evaluate the viability of wind resource in the reign, various aspects including environmental, technical and economic factors that affect the performance of the system must be investigated. Multi Criteria Decision Making (MCDM) is a subset of mathematic principle that assesses multiple competing factors in making a decision [26,27].

A number of studies have used MCDM methods to locate wind or wind-hydrogen power plants using a variety of criteria. Rezaei-Shouroki et al. [28] ranked the Fars province's cities in Iran using MCDM methods to produce hydrogen from wind energy. They reported that Izadkhast city was the most suitable place in the province for the exploitation of hydrogen from wind resources. Almutairi et al. [29] prioritized suitable cities of Yazd province for hydrogen production. They used Distance from Average Solution (EDAS) and Step-wise Weight Assessment Ratio Analysis (SWARA) techniques. The results revealed that Bahabad city had a better potential for developing wind farms to produce hydrogen. Rathi et al. [30] prioritized Indian states for developing wind projects using MCDM methods. Their assessment showed that Tamil Nadu was the most suitable state for developing wind projects in India. Other similar studies prioritized Saudi provinces to generate electricity from wind source [31], Afghan provinces

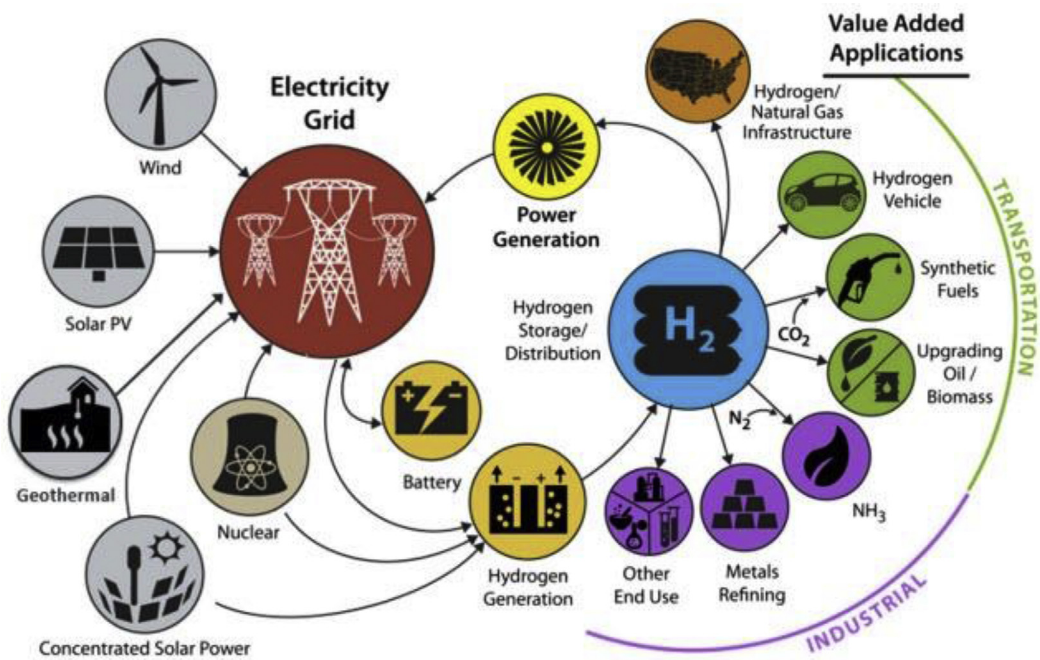

Fig. 1 – Different applications of hydrogen fuel [14].

to generate hydrogen from geothermal source [32], cities of Kerman province in Iran to produced hydrogen from solar energy [33].

In fact, the mentioned studies had selected the most suitable cities of a province or provinces of a country for the development of renewable-hydrogen projects, and as a result, the exact location of power plants was not known. Identifying suitable areas for wind farm construction involves the use of integrated results from surveys and complex studies and requires decisions that are subject to human error [2]. Geographic Information Systems (GIS) have become popular in renewable projects such as solar and wind assessments because of their ability to combine definitive data and eliminate areas with inappropriate targets [34]. In addition, using a combination of digital thematic maps with the application of stakeholder perspectives, public perception and expert opinion as input to MCDM method can help minimize these errors [2].

Many studies had identified suitable locations for the construction of wind farms using the GIS and GIS-MCDM method. Van Haaren et al. [35] located the wind farm in New York in the United States using the GIS method. They reported that wind turbines installed in New York were not located in suitable areas. Tegou et al. [36] located wind farms using the GIS-AHP method on the island of Lesvos in Greece. Their results showed that only 1.4% of the area has good wind potential. Georgiou et al. [37] located the wind farm in the province of Larnaca in Cyprus using the GIS-AHP method. They reported that only 0.1% of the area had a high potential for wind turbine construction. Aydin et al. [38] located the wind farm in western Turkey using GIS-MCDM method. They reported that the environmental criterion was the most important criterion in the study area. Baseer et al. [39] located the wind farm in Saudi Arabia. They first extracted wind GIS maps using IDW technique and then identified suitable areas by GIS-AHP method. They reported that Ras Tanura, Turaif and Al-Wajh were the most suitable areas for developing wind farms. Höfer et al. [40] located a wind farm in Städteregion Aachen, Germany. They reported that only 9.4% of the region had the potential to develop wind projects. Moradi et al. [2] located the construction of wind farms in Alborz province in Iran using GIS-AHP method. They reported that the south-eastern parts of the province had good potential for constructing wind farms.

However, very few studies had examined the location of renewable hydrogen power plants. For example, Messaoudi et al. [41] located the construction of a solar-hydrogen power plant in Algeria using the GIS-AHP method. They reported that 0.49% of the area had a very high potential for solar-hydrogen plant construction, and that the combination of GIS and MCDM was a powerful tool in locating hydrogen projects.

As mentioned in the literature, various methods such as feasibility study, MCDM, GIS and GIS-MCDM method have been used to identify the location of renewable power plants and especially wind farms. The feasibility method that has been used in many studies is based on one parameter. In other words, the most suitable place for the wind farm was the area that had the highest wind speed. MCDM-based methods have covered the weakness of feasibility approach and wind speed is one of the influential parameters. However, in the MCDM method, the choice of location for the construction of a wind farm can be considered only from a few options. These options can include choosing the most suitable city in a province or choosing the most suitable province in a country for the construction of renewable power plants. Therefore, MCDM methods do not determine the exact location of power plants. In GIS method, using geographical maps, the construction sites of the power plant are determined. But in this method, the main emphasis is on the constraints of construction. In other words, in this method, only unsuitable places for the construction of the power plant are removed. Therefore, only suitable areas for the construction of the power plant are identified and there is no priority between the areas for the construction of the power plant. The combination of GIS and MCDM methods fills the weakness of previous methods. Using constraints in GIS method, suitable areas are identified and then using criteria in MCDM method, suitable areas are prioritized. However, in the previous literature, it has been reported that the use of GIS-MCDM method for hydrogen production has been limited in studies (shown in Table 1). In order to fill the gap in the literature in the field of hydrogen production in wind energy, in the present study, the identification of constraints, criteria and application of GIS-MCDM method for hydrogen production from wind energy has been used. In general, the goals and innovations of the present study are as follows: (1) identifying the most relevant constrain and criteria in the field of locating hydrogen production from wind energy, (2) presenting the application of MCDM methods, especially the AHP approach in determining the weight of criteria, (3) determining the weight of criteria based on a survey of energy experts, (4) providing a combined GIS-MCDM method to address the weaknesses of previous research, (5) performing sensitivity analysis on the weight of criteria to increase the accuracy and stability of results and (6) utilizing the proposed approach to plan and provide a suitable place for hydrogen production from wind energy in Yazd province in Iran as a new case study.

Materials and methods

Study area

Yazd is one of Iran's 31 provinces, located in the country's central region. In the latest divisions of the country, the area of this province is 129,285 km^2 and includes 10 cities. According to the last census in 2016, the population of this province was equal to 1,138,533 people (340,657 households). Yazd province in central Iran is located between the longitude of 52° and 45 min to 56° and 30 min east and the latitudes of 29° and 48 min to 33° and 30 min north of the meridian of origin. This province is limited to Isfahan province from the north and west, Khorasan province from the northeast, Fars province from the southwest and Kerman province from the southeast. The population and industry density has been higher in these provinces and the construction of power plants in Yazd province can, in addition to supplying electricity and hydrogen within the province, also meet the needs of neighbor provinces.

Due to its location in the global arid belt, the province has cold winters, hot and dry summers. As a result, the increasing use of air conditioning systems is extremely high and usually leads to power outages [44]. In addition, the province of Yazd is one of Iran's major industrial centers. This province is the second mineral province of Iran and the most products of the industrial units of this province are textiles, ceramic tiles and machine-made carpets. Most of these industrial units are located in industrial towns in the suburbs of each city in this province. On the other hand, Yazd in central Iran was selected as a World Heritage Site at the 44th session of the UNESCO World Heritage Committee in Krakow, Poland. As a result, it hosts many tourists from all over the world. This emphasizes the necessary to expand new sources of energy with minimal environmental impact.

In the present research, the speed of wind from 11 meteorological stations in Yazd province were used. The location of 11 stations that are scattered throughout Yazd province is shown in Fig. 2.

MCDM approach

Selecting the best site for wind farms to generate electricity and hydrogen is a challenging task [45]. This needs

Table 1 – A summary of the most important previous studies in the field of wind energy/hydrogen production.

Researchers	Case study	Feasibility study of hydrogen production	GIS	MCDM	Sensitivity analysis
Genç et al. [17]	Antalya, Turkey	✓			
Iqbal et al. [18]	Sindh, Pakistan	✓			
Rodríguez et al. [19]	Cordoba, Argentina	✓			
Aiche-Hamane et al. [20]	Ghardaia, algeria	✓			
Alavi et al. [21]	Sistan and Baluchestan, Iran	✓			
Mostafaeipour et al. [22]	Fars, Iran	✓			
Rezaei-Shouroki et al. [28]	Fars, Iran	✓		✓	
Rathi et al. [30]	India			✓	✓
Van Haaren and Fthenakis [35]	New York State, USA		✓		
Noorollahi et al. [42]	Markazi, Iran		✓		
Tegou et al. [36]	Lesvos island, Greece		✓	✓	✓
Georgiou et al. [37]	Larnaca District, Cyprus		✓	✓	✓
Aydin et al. [38]	Western Turkey		✓	✓	
Baseer et al. [39]	Saudi Arabia		✓	✓	
Hansen [43]	Jutland, Denmark		✓	✓	
Höfer et al. [40]	Städteregion Aachen, Germany		✓	✓	✓
Moradi et al. [2]	Alborz, Iran		✓	✓	✓
Present study	Yazd, Iran	✓	✓	✓	✓

investigation of various options and comprehensive aspects to be evaluated [46]. To solve these kinds of problems, decision makers and researchers often use MCDM techniques [47]. Pohekar and Ramachandran [48] performed a study over 90 previous papers on MCDM application in sustainable energy planning. They reported that the most popular method was the AHP. The AHP technique was a systematic approach introduced by Saaty [49] in the 1970s to solve complex decision problems. The AHP method allows the participation of various stakeholders in energy-related fields, by performing pairwise comparisons and evaluation criteria, to determine their relative preference. The general steps of the AHP technique are as follows [49]:

Step 1: Select the criteria.

In the first step, appropriate criteria must be determined. The criteria were generally divided into three categories. The first category included technical aspect, the second category included economic aspect and the third category included environmental aspect.

Step 2: Form a matrix of pairwise comparisons.

In AHP decision making method, all comparisons are made in pairs. In other words, the relative importance of each criterion in relation to other criteria is examined. The matrix of two-by-two comparisons is in the form of equation (1):

$$A = [a_{ij}]_{n\times n}\ ,\ i,j = 1,2,\ldots,n$$
$$a_{ij} > 0\ ,\ a_{ji} = \frac{1}{a_{ij}},\ a_{ii} = 1\ for\ all\ i \tag{1}$$

where A_{ij} expresses the ratio of the importance of the ith to jth criteria. Therefore, the relative importance of the ith to jth criterion is the inverse of the relative importance of the jth to ith criterion. Table 2 has also been used to determine the relative importance of the criteria.

Step 3: Calculate the eigenvalue and the eigenvector of the matrix.

In order to calculate the relative weight (w_1, w_2, ... w_n) of the pairwise comparison matrix (Equation (1)), the equation (2) between the pairwise comparison matrix and the relative weight matrix is established:

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix} \cong \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \vdots & \vdots & \cdots & \vdots \\ w_n/w_1 & w_n/w_2 & \ldots & w_n/w_n \end{bmatrix} \tag{2}$$

$$AW = \lambda_{max} W$$

where $\lambda_{\max}$ is the maximum eigenvalue of the pairwise comparison matrix A and W is the relative weight vector of the criteria (w_1, w_2, ... w_n) proportional to the value of $\lambda_{\max}$.

Step 4: Compatibility index.

One of the features of the AHP method is the study of the degree of compatibility in the formed matrix. Saaty [49] had defined the compatibility index as the following equation:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{3}$$

The compatibility ratio is also defined as relation (4):

Table 2 – Relative importance of criteria in AHP method.

Degree of preference	Description
1	Both criteria are equally important
3	One criterion is relatively preferable to another
5	One criterion is preferable to another
7	One criterion is much preferable to another
9	One criterion is completely preferable to another
2, 4, 6, 8	Intermediate preference values
1.1–1.9	The preference conditions are very close

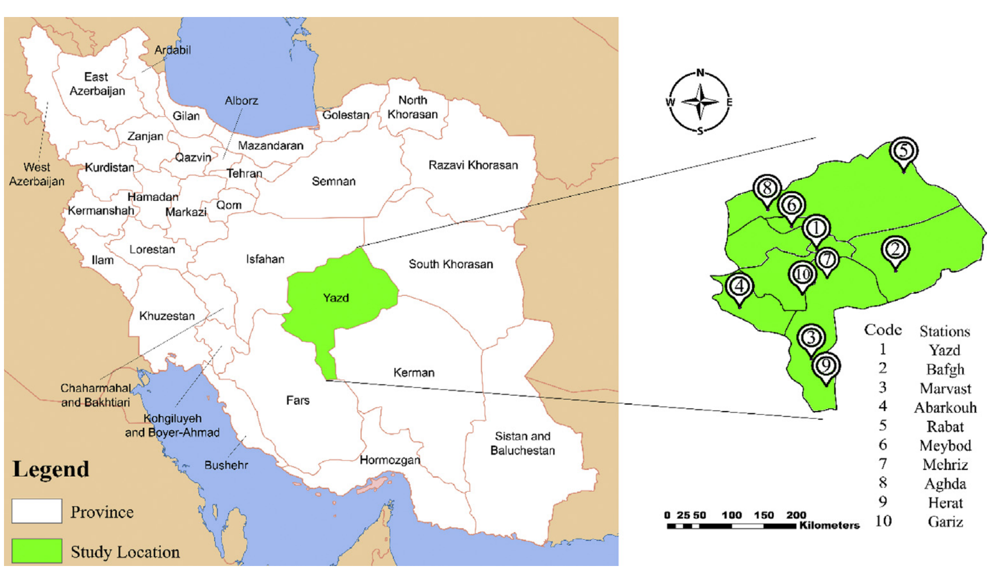

Fig. 2 – Geographical location of the study area and measurement stations.

$$CR = \frac{CI}{RI} \tag{4}$$

When the CR is less than 0.1, the compatibility of the system is acceptable and otherwise the judgments should be reconsidered.

GIS approach

After determining the scores of the criteria calculated from the AHP technique, the proper locations for constructing wind farm to produce power and hydrogen were identified as follows:

1. The EUCLIDEAN DISTANCE tool in ArcGIS is used to calculate distance-dependent criteria. Therefore, GIS maps for all criteria were prepared in the form of raster maps.
2. Each map has a different scale and should be normalized. Normalization is a step in the AHP method in which the value of each raster layer of the criteria changes from 0 to 1. There are several normalization methods and Linear Scale Transformation is the most common. Similarly, there are many types of Linear Scale Transformation methods. Methods maximum and minimum value range are more common [50]. Therefore, this method was used in this study. For positive criteria whose higher value was more desirable, normalization Equation (5) was used, and for negative criteria whose lower value was more desirable, Equation (6) was used:

$$x'_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \tag{5}$$

$$x'_{ij} = 1 - \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \tag{6}$$

3. In the next step, the RASTER CALCULATOR tool was used for algebraic calculations, which allowed the execution of algebraic expressions. At this stage, the weight of each criterion was applied according to the AHP technique for each raster cell.
4. Finally, the RECLASSIFY tool was used so that the value of each cell was equally divided into three categories with very high, medium and low potential.

Constraints and criteria for locating a wind-hydrogen power plant

The purpose of this study was to find possible locations to build a wind farm to generate power and hydrogen, and this was based on available data. Therefore, the necessary data were collected and evaluated before starting the analysis in a GIS environment. To obtain the recent existing data, access to the portals of various government agencies and other resources had been done.

The average speed of wind is not only an aspect that is considered when choosing a suitable location for wind farms, but also environmental and economic aspects are important in deciding on the location of a wind farm [51,52]. Based on interviews with experts and literature review, economic, physical and environmental aspects were classified as the main considered criteria and was done in a hierarchical process to obtain the desired result. The physical layer included parameters attached to terrestrial processes and geographical situations, including climatic conditions (average wind speed and hydrogen production rate) and topography (slope and altitude). The environmental layer included factors that were directly and indirectly related to the environment, including buffers to urban and rural residential reigns, buffers to facilities (roads, railways and airports) and landscapes (protected areas). The proximity to the market, such as roads, railways, main transmission lines and high-consumption hydrogen centers, mainly affects operating and capital costs, and therefore these factors were assessed at the economic layer.

Physical layer

The average wind speed, in almost all previous studies [39,40,51,53,54], had been the main criterion in determining the appropriate location of a wind farm. In the present research, the speed of wind from 11 meteorological stations in Yazd province were used. The location of 11 stations that are scattered throughout Yazd province is shown in Fig. 2.

The speed of wind at the desired height was calculated using the following equation [55]:

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{7}$$

$$\alpha = \frac{0.37 - 0.088\ \ln(v_1)}{1 - 0.088\ \ln\left(\frac{h_1}{10}\right)} \tag{8}$$

where v_2 is the speed of wind at the wind turbine hub height (h_2) and v_1 is the data measured at the height of h_1. All 11 meteorological stations are distributed almost equally throughout the province. In this study, the inverse distance weighted, or IDW, approach was employed to transform point data to raster format. A linear weight combination of a series of data points was used to calculate the magnitude of each cell. The IDW interpolation technique had been introduced as an accurate method. Ali et al. [56] evaluated five different interpolation techniques (i.e. kriging with 4 sub-types, spline with 3 sub-types, local polynomial interpolation, global polynomial interpolation, and IDW) for predicting speed of wind in Iraq. The forecasted wind speeds were compared with the actual wind speeds based on root mean square. Their finding showed that inverse distance weighted had the greatest result, and the conventional kriging method had the next rank.

In the next step, the rate of hydrogen generation from the wind resource must be calculated. The amount of H_2 generated from wind resource was estimated by modeling wind energy in the area. One of the most common wind modeling methods is the Weibull probability distribution function (WPDF) for statistical wind analysis [57]. Using the WPDF, the average annual electricity and hydrogen production can be easily calculated. The Weibull probability distribution function is defined as follows [25]:

$$f(\upsilon) = \frac{k}{c}\left(\frac{\upsilon}{c}\right)^{k-1} \exp\left(-\left(\frac{\upsilon}{c}\right)^{k}\right) \tag{9}$$

where v, c and k are the wind speed, shape factor and scale factor, respectively. The governing equations on the factors of shape and scale are as follows [58]:

$$c = \frac{\overline{\upsilon}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{10}$$

$$k = 0.83\overline{\upsilon}^{0.5} \tag{11}$$

where $\overline{\upsilon}$ represents the mean speed of wind at the wind turbine hub height and Γ represents the gamma function and is defined as follows:

$$\Gamma(x) = \int_{0}^{\infty} e^{-u} u^{x-1} du \tag{12}$$

Based on the obtained k and c parameters, the probability distribution function, i.e. Equation (9), was known. Based on this, the generated power of a wind turbine (P_{out}) can be determined. Capacity factor is a crucial element that shows the ratio of output power of wind turbine (P_{out}) to its rated power (P_n). The capacity factor (CF) is calculated as follows [25]:

$$C_F = \frac{P_{out}}{P_n} = \frac{e^{-\left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_0}{c}\right)^k} \tag{13}$$

where v_i, v_r and v_o are Cut in speed, rated speed and Cut out speed of wind turbine, respectively. Also, the amount of annual electricity production is calculated from the following equation:

$$E_{WT} = P_{out} \times 8760\text{h} \tag{14}$$

Also, the amount of hydrogen production can be obtained using the equation (15) [25]:

$$H_{WT} = \frac{E_{WT}}{Ec_{el}}\, \eta_{conv} \tag{15}$$

where η_{conv} is the rectifier efficiency, which is typically in the range of 80–95%, and Ec_{el} is the electrolysis energy consumption, which is about 5–6 kWh/Nm^2 [25].

Therefore, annual hydrogen production values were calculated at 11 stations and GIS maps were generated as described in the IDW linear interpolation technique. As a rule, the higher the wind speed and the annual hydrogen production, the more suitable the area was. However, according to previous studies [40,42,51,59], if the average wind speed was less than a certain amount, it will lead to the construction of a wind farm was not economically viable. Therefore, in this study, the wind speed of at least 4 m per second was selected as the limit of wind speed based on opinions of regional experts and the literature. In addition, the average cut-in speed for wind turbines is about 3–4 m/s.

Topography

Elevation and slope are the two main criteria of topography, and high elevation and slope are not recommended in almost all studies [51,59–61] for wind projects. The appropriate amount of slope for wind farms varied between 10 and 30% [39,51,59] in previous studies. Previous studies [42,51,61] had reported an elevation of 2000 m as the maximum elevation for wind farms in Iran, Turkey and Thailand. Based on this subject, the Elevations less than 2000 m and the maximum slope of 10% had been selected based on previous studies and the opinion of experts.

Environmental aspects

Residential buffers had been considered in all similar studies [51,62,63] to generate power from wind energy. These are needful to prevent noise in human life. At least one 500-m rural-urban residential buffer had been suggested for locating wind farm in previous studies [51,64]. Therefore, in this study, 1000 m buffers and 500 m buffers were approved for urban and rural areas, respectively.

In all previous studies aimed at determining the best sites for wind farms, the distance to airports was taken into account, because wind turbines interfered with signals of monitoring radar, which were very important for managing air traffic [56]. Other researches [42,65] had suggested distances of 2500 m and 3000 m, and in this study the second distance seemed safer. Buffers are essential for protected areas to avoid harm to costly technology as well as to preserve natural and biodiversity resources. Therefore, in this study, a buffer of 300 m from protected areas to keep away from bats and birds and 1000 m from tourist areas had been considered.

Economic aspects

Proximity to transmission lines and roads is economically important in energy projects [42,51,62], as longer distances to transmission lines and roads may lead to increased power line losses and project's costs. Therefore, areas that were more than 10 km away from the mentioned cases were not included in this study [51]. In addition, to prevent damage to expensive equipment, buffer 500 m of roads and railways, 250 m of power transmission lines and 500 m of faults had been considered.

The constrains considered in the present study are listed in Table 3.

In the present study, the considered criteria had been concluded in accordance with international and national guidelines and after huge literature review. In addition, these criteria were approved by eleven experts with the aim of minimizing personal conflict and prejudice. The selected decision makers were all energy experts in Iran, researchers, university professors and professional engineers were fully aware of hydrogen and wind energy programs, as well as the terrestrial situation of the considered area. The criteria for evaluating the most suitable site using the MCDM method are shown in Table 4.

Results and discussion

Wind speed

The average wind speed for the 11 stations is shown in Table 5. The maximum and minimum of wind speed occurred at Herat

Table 3 – Set of constraints intended for the construction of wind-hydrogen power plants.

Categories	Data	Description
Physical constraints	Wind speed	Wind speed less than 4 m/s
	Dem	Areas with an elevation of more than 2000 m
	Slope	Areas with a slope greater than 10%
Economic constraints	Roads	Areas with a distance of less than 500 m
	Railways	Areas with a distance of less than 500 m
	Transmission line	Areas with a distance of less than 250 m
	Fault	Areas with a distance of less than 500 m
Environmental constraints	Airport	Areas with a distance of less than 3000 m
	Settlement area	Areas with a distance of less than 2000 m
	Protected area	Areas with a distance of less than 300 m
	Cultural-tourism area	Areas with a distance of less than 700 m

and Bafgh station, respectively. According to previous studies and the use of turbines at 100 m, wind speed data should be transferred to an altitude of 100 m. From the extrapolated wind speed values at 100 m, using the IDW method, the wind GIS map at 100 m is shown in Fig. 3.

Potential of hydrogen production

To evaluate the potential of hydrogen production in the region, four different wind turbines had been evaluated. In this study, Wind turbine with a capacity of 2 MW had been used. The specifications of the considered turbines are given in Table 6.

As mentioned before, the highest efficiency was related to the wind turbine, which had the highest CF coefficient. The calculated CF coefficients for different turbines at all stations are given in Table 7. As it was known, the Gamesa G80 turbine had the highest amount of CF and the results of the present study were based on such a turbine.

Table 5 – Average measured wind speed, α coefficient, and approximate wind speed at 100 m and Weibull parameters.

Stations	V_{10} (m/s)	α coefficient	V_{100} (m/s)	k	c
Yazd	2.91	0.28	5.49	1.946	6.196
Bafgh	2.71	0.28	5.19	1.891	5.849
Marvast	3.91	0.25	6.95	2.189	7.851
Abarkouh	3.24	0.27	5.99	2.031	6.756
Rabat	3.33	0.26	6.12	2.053	6.906
Meybod	3.50	0.26	6.37	2.094	7.187
Mehriz	3.33	0.26	6.12	2.053	6.906
Aghda	3.84	0.25	6.85	2.173	7.739
Herat	5.05	0.23	8.53	2.424	9.617
Gariz	3.95	0.25	7.01	2.198	7.915

Table 4 – Criteria considered for locating the construction of wind-hydrogen power plant.

Categories	Criteria	Description	References
Technical	Wind speed	The higher the wind speed, the greater the potential for electricity and hydrogen generation. Therefore, the behavior of this criterion is positive.	[39,51,66]
	Hydrogen production potential	The greater the potential for hydrogen production in the region, the more suitable the site is for the construction of a power plant. Therefore, the behavior of this criterion is positive.	[32,41]
	Slope	The slope criterion is an important criterion for economic and transportation reasons. Therefore, its type is negative.	[2,40,67]
Economic	Proximity to transmission line	Proximity to the adjacent network is significant for the feeder line as well as power loss (shorter, better). Therefore, the shorter the distance, the more suitable the area. So its behavior is negative.	[2]
	Proximity to urban area	The location of wind farms near urban and high-consumption areas has economic benefits. Therefore, with wind farms located near high-consumption settlements, wind farm energy is needed to transmit power to fewer transmission lines, thus reducing the cost of delivering energy to customers. So the type is negative.	[2]
	Proximity to roads	Proximity to major roads is essential because transporting massive turbines can be complicated and prohibited. The distance from the potential wind farm to major roads or railways should be reduced to reduce costs. In almost all studies, areas close to roads are more suitable for wind farms. Therefore, its type is negative.	[41]
	Proximity to railways	This criterion is similar to the criterion of distance to the road.	[41]
	Proximity to high hydrogen demand	As mentioned before, the industrial centers in this province are located in the suburbs in industrial towns. Therefore, shorter distances to these centers are economically necessary as the most demanding consumer of hydrogen. Therefore, its type is negative.	[32]

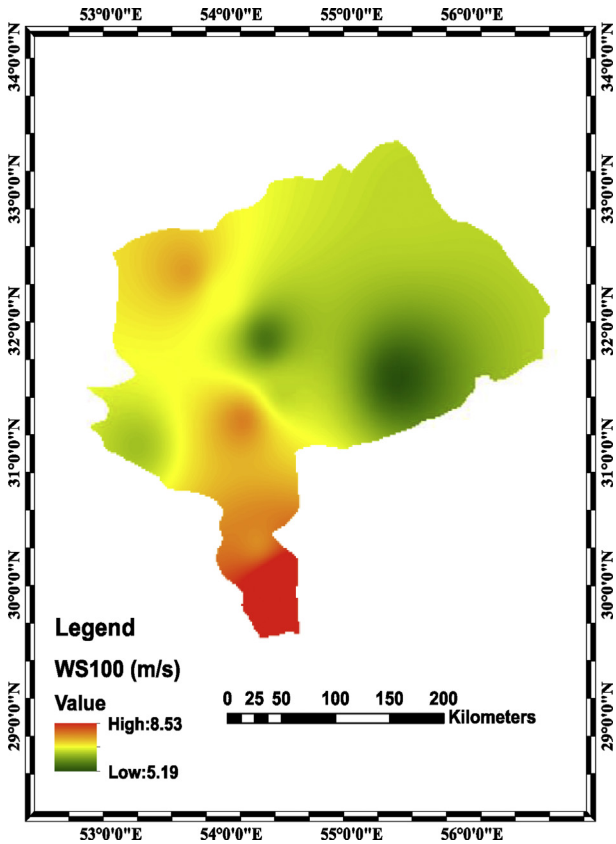

Fig. 3 – Spatial distribution of average wind speed at 100 m based on IDW method.

Therefore, considering the Gamesa G80 turbine, the electricity generated and the amount of hydrogen production rate calculated at all stations are given in Table 8. The highest capacity of hydrogen and electricity generation was 128.6 tons per year and 7946 MWh per year in Herat station and the minimum was 53.6 tons per year and 3312.6 MWh per year in Bafgh station, which indicated the high potential of wind energy and consequently the high potential of hydrogen production in this province.

To produce a raster map of hydrogen production potential in this province, the annual amount of hydrogen calculated in Table 8 was used for each station and the IDW method was

Table 6 – Characteristics of turbines of wind considered in this study.

Turbine model	Rated power (MW)	Hub Height (m)	Cut-in speed (m/s)	Rated speed (m/s)	Cut out speed (m/s)
Beijing North BZD80-2000	2	100	3.5	13.5	25
Enercon E–70 E4 2.000	2	99	2.5	13.5	34
Gamesa G80	2	100	3.5	12	25
Vestas V80 –2.0	2	100	4	15	25

Table 7 – Calculated CF values for four wind turbines at all stations.

Stations	Beijing North BZD80-2000	Enercon E-70 E4 2.000	Gamesa G80	Vestas V80-2.0
Yazd	16.80	18.92	21.06	12.58
Bafgh	15.10	17.31	18.91	11.22
Marvast	25.94	27.56	32.35	20.01
Abarkouh	19.70	21.67	24.71	14.91
Rabat	20.51	22.44	25.72	15.57
Meybod	22.07	23.91	27.65	16.83
Mehriz	20.51	22.44	25.72	15.57
Aghda	25.27	26.93	31.55	19.46
Herat	37.21	38.30	45.35	29.62
Gariz	26.33	27.93	32.81	20.33

Table 8 – Feasibility results of construction of wind-hydrogen power plants in each station based on electricity and hydrogen production in one year.

Stations	Annual energy production (MWh)	Annual hydrogen production
Yazd	3689.4	59.7
Bafgh	3312.6	53.6
Marvast	5668.2	91.8
Abarkouh	4328.4	70.1
Rabat	4505.7	72.9
Meybod	4843.5	78.4
Mehriz	4505.7	72.9
Aghda	5526.7	89.5
Herat	7946.0	128.6
Gariz	5749.0	93.1

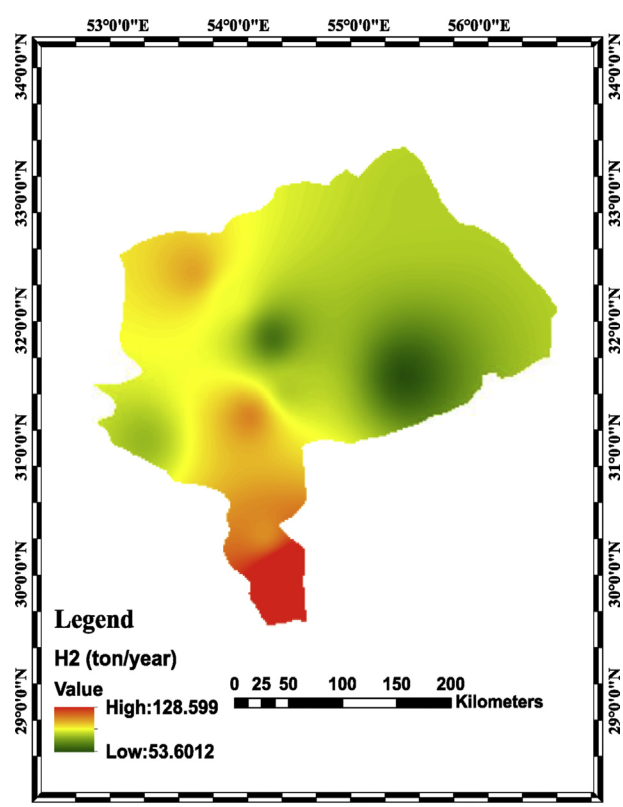

Fig. 4 – Spatial distribution of hydrogen production potential in ton/yr using IDW method.

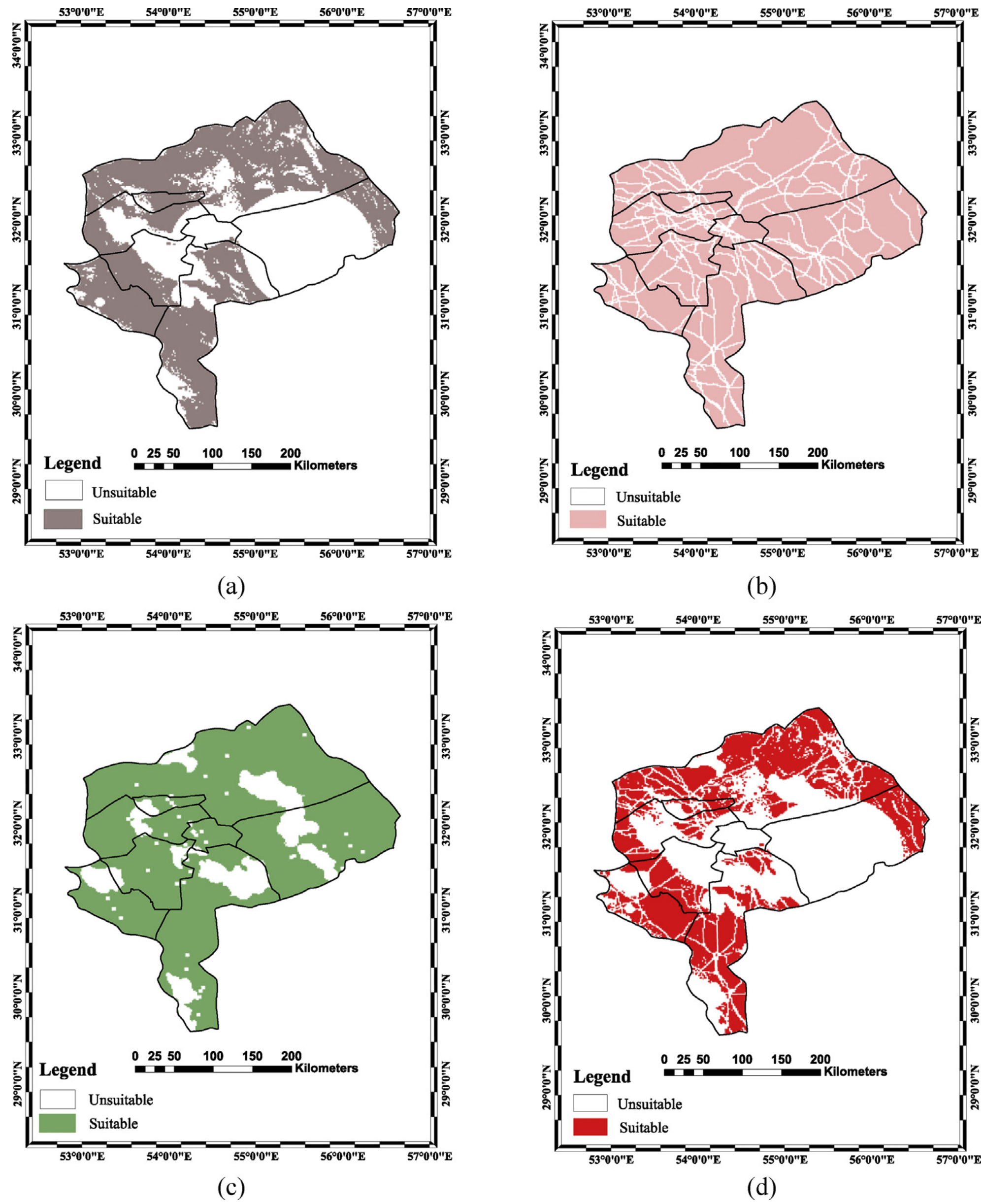

Fig. 5 – Constraints intended for the construction of power-hydrogen plants driven by wind energy: a) physical constraints, b) economic constraints, c) environmental constraints and d) all constraints.

used for interpolation. The results of the raster map of hydrogen production potential are shown in Fig. 4.

Constraints on GIS maps

Based on the constraints listed in Table 4, the GIS maps of physical, economic, and environmental constraints are shown in Fig. 5. Taking into account all the constraints, suitable areas for the construction of wind farms are shown in Fig. 5-d.

MCDM evaluation

Comparison of each criterion and sub-criterion was done based on the opinion of experts and the results of AHP method were performed using Matlab software as shown in Tables 9–12.

Table 9 shows the comparison between integrated decisions to compare suitable locations for power-hydrogen production. As it was known, according to the opinion of experts, compared to technical criteria, economic criteria had a greater preference of 2.15.

Table 10 shows the expert opinions in the economic subcriterion. The comparison showed that proximity to urban areas prefer more than the following other criteria, followed by distance to the centers with high hydrogen consumption.

Table 11 shows the expert opinions in the technical subcriterion. According to Table 11, average wind speed sub criteria had a higher preference in comparison to hydrogen production potential (1.58) and slope (3).

Table 9 – Summarizing the opinions of experts in the main criteria.

Suitable sites for construction of wind-hydrogen power plant	Economic	Technical
Economic	1	2.15
Technical	0.47	1

Table 12 shows the weight of the criteria obtained from the pairwise comparison of the criteria and sub-criteria. Economic criteria had the highest importance with a value of 0.681 and as a result, technical criteria had a value of 0.319. The most significant sub-criterion was the proximity to urban areas and the least significant sub-criterion was the proximity to power transmission lines among the sub-criteria. Also, the calculated CR and CI index in AHP method was in the acceptable range.

Final evaluation of suitable areas

The final locations were determined based on normalized GIS maps from weighted criteria taking into account the constraints that allowed us to divide the considered areas on a gradation between very suitable, appropriate medium, slightly suitable and unsuitable. In that cell that had a higher magnitude related to the more proper region for hydrogen generation. Fig. 6 shows this classification of areas. Red areas were the most suitable places to build a wind-hydrogen power plant. These areas were mostly in the southern and central parts of the province. More precisely, these areas included the west of Ardakan, the north of Mehriz, Ashkzar, Meybod, the south of Taft, the central part of Abarkooh and the south of Khatam city. However, Yazd city, many parts of Ardakan, Bafgh and Bahabad did not have good potential.

Sensitivity analysis

In MCDM techniques with the "what if" decision, sensitivity analysis is recommended as a means of examining the stability of results against the subjective judgment of experts [41]. By doing this, the weight scenarios of different criteria were investigated and their effect on the suitability of land for constructing wind farm was investigated. Thus, two scenarios including equal weight and higher economic weight [41] were considered in the present research, and the result are shown in Fig. 7.

The weights of all the criteria were identical in the first scenario; each criterion's weight was 0.125. The results (Fig. 7a) showed that there was not much change in suitable areas. The only significant difference was related to the elimination of suitable areas in Abarkooh city, which was due to the decrease in the effect of proximity to urban areas, high-consumption hydrogen centers and the road, and had changed from high suitability areas to moderate suitability areas. However, there

Table 10 – Summary of expert opinions in the economic sub-criterion.

Economic criteria	Distance to urban areas	Distance to high-consumption hydrogen centers	Distance to the roads	Distance to the railways	Distance to power transmission lines
Distance to urban areas	1	1.58	2.15	2.89	4.33
Distance to high-consumption hydrogen centers	0.633	1	1.91	2.15	3.63
Distance to the roads	0.465	0.524	1	1.58	3
Distance to the railways	0.346	0.465	0.633	1	3
Distance to power transmission lines	0.231	0.275	0.333	0.333	1

Table 11 – Summarizing the opinions of experts under the technical criteria.

Technical criteria	Wind speed	Hydrogen production potential	Slope
Wind speed	1	1.58	3
Hydrogen production potential	0.633	1	2.89
Slope	0.333	0.346	1

Table 12 – Final results of AHP method.

Criteria	Weight	Sub-criteria	Weight	CI and CR	Final weight
Economic criteria	0.6814	Distance to urban areas	0.3597	CI = 0.0175, CR = 0.0156	0.245
		Distance to high-consumption hydrogen centers	0.2664		0.182
		Distance to the roads	0.1749		0.119
		Distance to the railways	0.1352		0.092
		Distance to power transmission lines	0.0638		0.043
Technical criteria	0.3186	Wind speed	0.4956	CI = 0.0096, CR = 0.0166	0.158
		Hydrogen production potential	0.3608		0.115
		Slope	0.1436		0.046

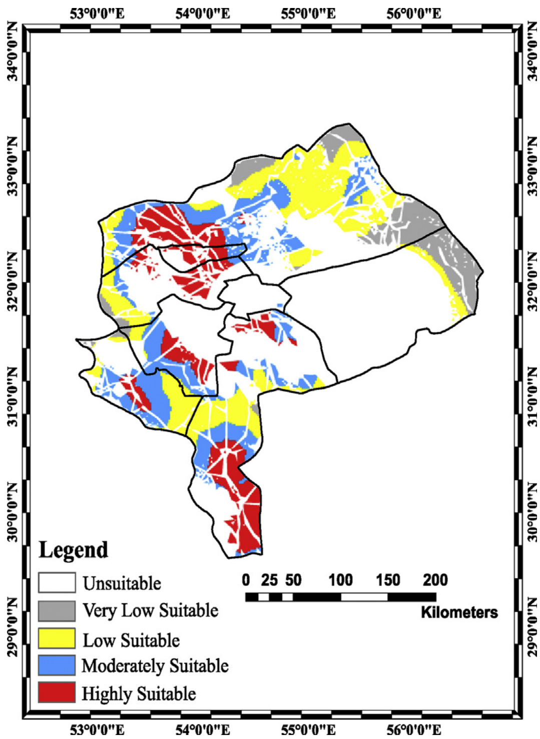

Fig. 6 – Final results of identifying the most suitable places based on GIS-MCDM method for construction of power -hydrogen plant driven by wind energy.

was not much difference in areas. In the second scenario (Fig. 7b), economic criteria had shown a higher value than other criteria. The most observed difference was related to Khatam city. The reason was due to the reduction of weight of technical parameters, because as mentioned before, Herat station had the highest wind speed and hydrogen production potential and should be located in the highly suitable area, but due to the low weight allocated, it had caused to moderate suitable areas. In general, the results did not change much with the results based on the opinion of experts.

Conclusions

Selecting suitable locations for electrolyzer-wind turbine systems to generate power and hydrogen is a complex issue and involves a variety of aspects, including environmental, economic, technical, and social. Not only areas with high wind energy potential (hydrogen potential) as a suitable area for the construction of a wind farm to produce hydrogen, but also many other criteria are effective in determining the appropriate location of the wind farm. Therefore, it is necessary to use MCDM-based methods. In the present study, a combination of GIS and MCDM methods for spatial identification of wind farms for hydrogen production in central Iran had been investigated. The AHP technique was used to determine the relative weight of the criteria. On the other hand, GIS method had been used to determine the constraints and produce raster maps for each criterion. Finally, the combination of GIS and MCDM methods, the suitability map was determined based on technical, economic and environmental aspects. Each of the criteria included sub-criteria, average wind speed, hydrogen production potential, land slope for technical criteria and distance to electricity grid, distance to urban areas, distance to road, distance to railway and distance to centers of High hydrogen consumption for economic criteria. The most achievements of the present study are as follows:

- ❖ Evaluation of different wind turbines with a capacity of 2 MW has shown that Gamesa G80 turbine is the most suitable wind turbine in different areas in Yazd province.

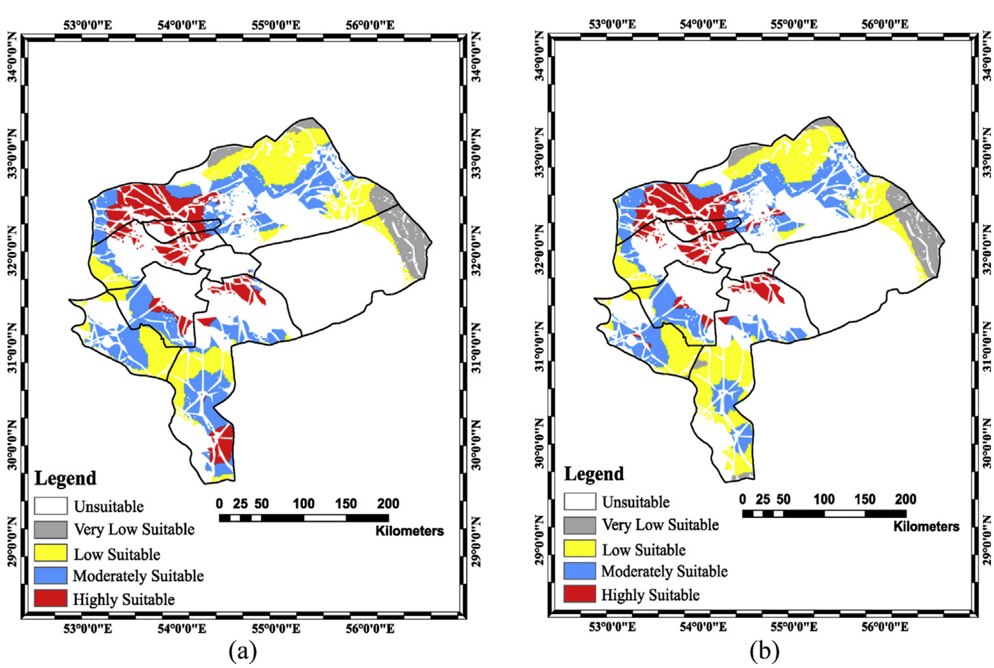

Fig. 7 – Sensitivity analysis on the weight of criteria: a) Scenario 1 and b) Scenario 2.

- ❖ Technical assessments have shown that the use of 2 MW wind turbines in Yazd province leads to the production of 128.6 tons per year and 7946 MWh per year.
- ❖ Economic factors have a greater impact on the selection of a suitable location for the construction of a wind-hydrogen power plant than technical factors.
- ❖ Distance to urban areas was determined as the most important economic criterion and wind speed as the most important technical criterion in locating a wind-hydrogen power plant.
- ❖ GIS-MCDM evaluation has shown that the southern and central regions of Yazd province are the most suitable regions for the development of wind energy for hydrogen production. More precisely, these areas included the west of Ardakan, the north of Mehriz, Ashkzar, Meybod, the south of Taft, the central part of Abarkooh and the south of Khatam city.
- ❖ Sensitivity analysis has also shown that if the economic criteria are important, the southern region of Yazd is not a very suitable area for the construction of wind-hydrogen power plant.

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.

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