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# Prioritizing the locations for hydrogen production using a hybrid wind-solar system: A case study

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**Abstract.** Energy is a major component of almost all economic, production, and service activities, and rapid population growth, urbanization and industrialization have led to ever growing demand for energy. Limited energy resources and increasingly evident environmental effects of fossil fuel consumption has led to a growing awareness about the importance of further use of renewable energy sources in the countries energy portfolio. Renewable hydrogen production is a convenient method for storage of unstable renewable energy sources such as wind and solar energy for use in other place or time. In this study, suitability of 25 cities located in Iran's western region for renewable hydrogen production are evaluated by multi-criteria decision making techniques including TOPSIS, VIKOR, ELECTRE, SAW, Fuzzy TOPSIS, and also hybrid ranking techniques. The choice of suitable location for the centralized renewable hydrogen production is associated with various technical, economic, social, geographic, and political criteria. This paper describes the criteria affecting the hydrogen production potential in the study region. Determined criteria are weighted with Shannon entropy method, and Angstrom model and wind power model are used to estimate respectively the solar and wind energy production potential in each city and each month. Assuming the use of proton exchange membrane electrolyzer for hydrogen production, the renewable hydrogen production potential of each city is then estimated based on the obtained wind and solar energy generation potentials. The rankings obtained with MCDMs show that Kermanshah is the best option for renewable hydrogen production, and evaluation of renewable hydrogen production capacities show that Gilangharb has the highest capacity among the studied cities.

**Keywords:** renewable energy; multi-criteria decision making; solar energy; wind energy; ranking; renewable hydrogen

## 1. Introduction

Energy is a basic prerequisite for economic, industrial and scientific development of countries, and plays a key role in production and provision of all commodities and services (Muneer *et al.* 2003). Supplying reliable and sustainable energy is one of the greatest challenges of the present era (Sen and Bhattacharyya 2014). Today, the majority of world's energy demand is met by fossil fuels such as oil, gas and coal (Dalton *et al.* 2008). Population growth, and rapid urbanization and industrialization of societies have also led to rapid growth of energy demand. Meeting this demand

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means consuming more fossil fuels, which leads to worsening environmental pollution and its resulting effects. Moreover, fossil resources are limited and are depleting rapidly, and this trend will lead to imbalance between energy production and demand in the future (Erdinc and Uzunoglu 2012). The necessity of replacing fossil fuels with reliable and environment-friendly energy sources highlights the importance of more effective use of renewable energy. The problems and limitations associated with the use of renewable energy sources hinder the growth in global use of this type of energy, especially in Iran (www.suna.org.ir). One of the major problems of renewable energy is that it is not available at all times and locations; the sun does not shine at all hours and the wind does not always blow. Therefore, for these renewable energies to be used at desired times and locations, they need to be stored (www.suna.org.ir). Integrating the production of unstable renewable energy sources, especially wind and solar energy, with renewable hydrogen production technology can facilitate the use of renewable energies instead of fossil fuels (www.renewableenergyworld.com). The electricity generated by renewable and clean energy sources can be stored as hydrogen gas produced by water electrolysis (Gupta 2008, Dagdougui *et al.* 2011 and Abbasi and Abbasi 2011) in other word, we can use hydrogen as a vessel to store energy so that we can consume it in place and time of our desire (ourworld.unu.edu). Stored hydrogen can be converted into electrical, thermal and eventually other types of energy. Most importantly, converting hydrogen into energy produces pure water and has no adverse environmental effect (Dagdougui *et al.* 2011). This technology can be used to overcome the limitations of fossil fuel. Hydrogen is the simplest element discovered by man. Each atom of Hydrogen has one proton and one neutron and it is one of the most abundant elements on the Earth's surface. Gaseous hydrogen, $H_2$, does not exist in nature in pure form and is always found in combination with other elements. The major examples are the combination of hydrogen with oxygen or $H_2O$ (water) and the combination of hydrogen with carbon, which creates different hydrocarbons such as $CH_4$ (Methane), coal and Oil. Thus, Hydrogen can be extracted and separated from other elements through different methods. What makes hydrogen so important in the energy market is its role as a secondary source of energy (Dagdougui *et al.* 2011). Secondary sources of energy are energy carriers that are not extracted directly from natural resources but rather from a process of converting primary energies. Various petroleum products, refined gas and electrical energy (electricity) are considered secondary energy sources (Gupta 2008). To transmit any type of energy to another place, it must be converted into a secondary energy source; one simple example is the process of converting fossil energy to electrical energy in conventional power plants. Hydrogen, as a secondary energy source, can deliver the renewable energy to the demand. In other words, hydrogen can store the energy generated from renewable sources and then act as the fuel in transportation system, for heating, in electricity production, and in chemical processes (Abbasi and Abbasi 2011). To extract hydrogen from chemical compounds, its molecular links must be broken, and doing so needs an amount of energy (e.g., water electrolysis process needs electrical energy). When carbon elements are not involved in hydrogen production, the produced hydrogen is called renewable hydrogen (Abbasi and Abbasi 2011 and www.ourworld.unu.edu).

Deokattey *et al*. (2013) provided a thorough review about production of hydrogen using High Temperature Reactors (HTR). They found that Korea, Japan, USA, and Europe were active in doing research toward hydrogen production using different cycles like: The Hybrid Copper Chloride cycle multi-stage thermo-chemical cycle; The Hybrid Sulphur (HyS) cycle or Westinghouse cycle; and The Sulfur-Iodine (SI) Cycle.

Many scientists are trying to find a strategy to optimize production of energy in the future.

Bioenergy is an important biological source of clean energy. Bio-hydrogen is also a source of renewable energy which refers as an energy carrier gas (Kose and Oncel 2014). Márquez et al. (2014) investigated production of photocatalytic hydrogen by water splitting using catalysts under UV-vis light irradiation. They mentioned that Photo catalytic water splitting for hydrogen production is a clean and renewable process that involve a semiconductor material under sun radiation and ambient pressure and temperature. Kar and Gopakumar (2015) investigated the renewable energy development in India. India as well as many other countries is trying to invest on renewables, but wind and solar are two main renewables which have been more popular than other sources. Mukhopadhyay and Ghosh (2016) investigated the use of solar tower combined cycle plant with thermal storage. It was mentioned that the sun is capable providing almost 1.8×1011 MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. Carnevale *et al*. (2016) compared the cost and environmental impacts of wind and solar energy for electricity production. From the economic and environmental aspects, they found that two technologies are economically feasible and also help us to have a cleaner environment. Ennetta *et al*. (2016) performed feasibility study about hydrogen enriched methane flames simulations. There have also been other works by researchers regarding modeling and optimization using solar coleectors and biodiesel too (Ismail *et al*. 2016, Dhillon and Tan 2016).

Mostafaeipour *et al*. (2016), investigated feasibility of wind energy for producing of hydrogen for province of Fars in central part of Iran. They concluded that city of Abadeh was the best option for this purpose. There are many research works related to wind and solar energy as renewable sources of energy which evaluated potential of generating electricity in Iran (Mostafaeipour and Abesi 2010, Shamshirband *et al*. 2015a, Mohammadi *et al*. 2016). Clearly, solar as a major renewable energy source could be used to generate electricity to produce hydrogen (Shamshirband *et al*. 2015b). Qolipour *et al*. (2016) performed a research about hybrid wind-solar for electricity production in Iran. Alavi *et al*. (2016) investigated production of hydrogen for southeastern part of Iran which got positive results. Pooranian *et al.* (2016) investigated a smart grid connected system for future which could be connected to a small-scale network and self-contained micro-grids. Results of their research indicated that it is able to lower the operating power and pollution emission. Cordeschi *et al*. (2014) developed a new model that is able to operate under hard per-job delay-constraints. A major advantage of the proposed model was the capability to adapt to the time varying statistical features of the proposed workload without requiring a priori assumption and/or knowledge about the statistics of the processed data.

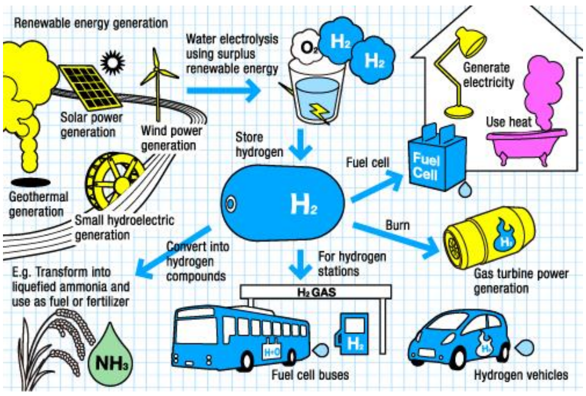



Fig. 1 production-consumption process of renewable hydrogen (www.thinktheearth.net)

Fig. 1 shows the production-consumption process of renewable hydrogen, which consists of 3 steps:

1. Producing energy from renewable sources such as solar, wind and geothermal energy and using the produced electricity to separate hydrogen from oxygen (of water) in an electrolysis process.
2. Storing hydrogen in pressure vessels.
3. Using the stored hydrogen in fuel cells (producing electricity by combining hydrogen with oxygen) as automobile fuel or to supply water, power and heating, and also to produce chemicals such as ammonia.

## 2. Study area

The study area includes all 25 cities and towns in the Kurdistan, Kermanshah and Ilam provinces in the western area of Iran (Fig. 2), and covers an area of 71,723 square kilometers. This area is located between north latitudes 32°6' and 36°26', and between east longitudes 45°27' and 48°. This area is bound on one side by Zagros Mountains and by Iraq border on the other side. According to the latest general census in 2011, this area has a population of over 3,996,471 people (www.thinktheearth.net). All electrical energy in this area is supplied and distributed by west regional electric company (www.amar.org.ir). The geographical boundaries of the west regional electricity are limited to Kermanshah, Kurdistan and Ilam. Table 1 shows the geographical coordinates of the study area. The energy of this area is supplied from the following sources: Sanandaj combined cycle power plant, Islamabad gas power plant, Bisotun steam power plant, Sanandaj and Ilam diesel power plants, Piran hydroelectric power plant, Azad dam, and Darreh Shahr Seymareh dam (www.ghrec.co.ir). The above sources are controlled by a dispatching-control center (connecting all power plants to the grid). Kermanshah, Kurdistan and Ilam provinces are also the largest Kurdish populated areas in Iran.

Table 1 Geographical coordinates of cities

| Sites | Latitude N | Longitude E | Altitude [m] |
|---|---|---|---|
| Abdanan | 32° 59' 19.03" | 47° 25' 28.32" | 878.85 |
| Baneh | 35° 59' 54.96" | 45° 52' 56.43" | 1526.52 |
| Bijar | 35° 31' 15.96" | 46° 10' 32.45" | 1309.00 |
| Darrehshahr | 33° 8' 38.04" | 47° 22' 58.42" | 661.51 |
| Dehloran | 32° 41' 31.91" | 47° 16' 4.64" | 222.42 |
| Divandarreh | 35° 54' 49.15" | 47° 1' 36.07" | 1844.94 |
| Eevan | 33° 49' 38.50" | 46° 18' 35.81" | 336.70 |
| Eslamabadgharb | 34° 6' 47.47" | 46° 31' 40.34" | 1335.05 |
| Gasrshirin | 34° 30' 57.25" | 45° 34' 39.67" | 354.25 |
| Ghorveh | 35° 10' 4.41" | 47° 48' 13.78" | 1907.05 |
| Gilangharb | 34° 8' 22.96" | 45° 55' 14.19" | 802.41 |
| Harsin | 34° 16' 18.89" | 47° 36' 16.62" | 1567.97 |
| Ilam | 33° 17' 44.74" | 46° 40' 13.92" | 1472.84 |

Table 1 Geographical coordinates of cities

| Sites | Latitude N | Longitude E | Altitude [m] |
|---|---|---|---|
| Kamyaran | 34° 47' 44.07" | 46° 56' 12.50" | 1468.44 |
| Kangavar | 34° 30' 25.53" | 47° 57' 23.25" | 1503.30 |
| Kermanshah | 34° 19' 39.69" | 47° 4' 39.97" | 1341.70 |
| Marivan | 35° 31' 15.96" | 46° 10' 32.45" | 1309.00 |
| Mehran | 33° 7' 3.59" | 46° 10' 23.85" | 153.97 |
| Paveh | 35° 2' 34.84" | 46° 21' 18.98" | 1528.68 |
| Ravansar | 34° 48' 22.59" | 46° 29' 31.92" | 1313.41 |
| Saghez | 36° 14' 20.20" | 46° 16' 40.70" | 1454.44 |
| Sahneh | 34° 28' 26.53" | 47° 41' 41.10" | 1348.17 |
| Sanandej | 35° 19' 18.75" | 46° 59' 10.19" | 1538.43 |
| Sarpolzahab | 34° 27' 5.02" | 45° 51' 40.35" | 559.53 |
| Songhor | 34° 46' 40.42" | 47° 35' 46.78" | 1690.33 |

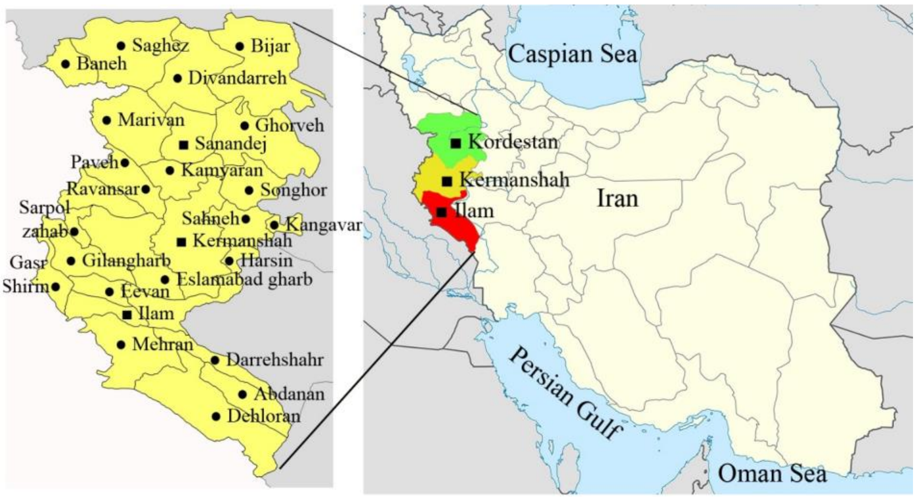



Fig. 2 The study area

## 3. Research method

In this study, two groups of methods are used. The first group consists of multi-criteria decision making methods including TOPSIS, VIKOR, ELECTRE, Fuzzy TOPSIS and Simple Additive Weighting (SAW). Methods of the second group are used to estimate solar energy, wind energy and the potential for renewable hydrogen production.

### *3.1 Multi-criteria decision making techniques*

Multi-Criteria Decision Making or MCDM techniques try to determine how to make the best decision or choose the best alternative based on available information in regard to matters of interest (Chong *et al.* 2017). MCDMs assess several alternatives by considering several criteria to select the alternative with the highest utility (Alinezhad and Amini 2011). MCDMs can be applied to certain decisions (of the preference type) such as evaluation, prioritization and selecting from the available alternatives (sometimes based on conflicting criteria).

#### *3.1.1 TOPSIS*

Introduced by Hwang Wein in 1981, TOPSIS is one of the techniques of Multi-Criteria Decision Making (MCDM) and one of the classic compensatory methods for solving prioritization problems [14]. This technique is based on the notion that selected alternative must have minimum distance from the positive ideal solution (best case scenario) and maximum distance from the negative ideal solution (worst case scenario) (Alinezhad and Amini 2011).

Implementation of TOPSIS consists of following steps (Jahanshahloo *et al.* 2006 and Opricovic and Tzeng 2004):

Step One: Creating the decision matrix

Step Two: Calculating the normalized decision matrix through vector norm method.

Step Three: Calculating the weight matrix with a weighting method

Step Four: Calculating the normalized weighted matrix V using the following general formula (Jahanshahloo *et al*. 2006)

$$V = N \times W_{1\times n} \tag{1}$$

Step Five: Determining the positive ideal solution $V_j^+$; the greatest value is for positive criteria and the lowest value is for negative criteria. In other words, we create a vector consisting of the best values for each criterion (Opricovic and Tzeng 2004).

Determining the positive ideal solution $V_j^-$; the greatest value is for the negative criteria and the lowest value is for the positive criteria. In other words, we create a vector consisting of the worst values for each criterion (Opricovic and Tzeng 2004).

Step Six: Calculating the Euclidean distance of each alternative to the positive and negative ideal points (Alinezhad and Amini 2011).

The Euclidean distance from the positive ideal solution ($di^+$) is calculated using the following equation

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2} \quad , \; i = 1,2,3,\dots,m \tag{2}$$

The Euclidean distance from the positive ideal solution ($di^-$) is calculated using the following equation (Alinezhad and Amini 2011)

$$d_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \quad , \; i = 1,2,3,\dots,m \tag{3}$$

Step Seven: Determining the relative closeness of each alternative to the ideal solution using the following equation (Opricovic and Tzeng 2004)

$$CL_i^* = \frac{d_i^-}{d_i^- + d_i^+} \tag{4}$$

Step Eight: Ranking the alternatives based on the greatest $CL_i^*$ (Opricovic and Tzeng 2004).

### *3.1.2 SAW method*

This method is one of the oldest and simplest scoring methods in MCDM (Peng *et al.* 2016).

The steps of this method are as follows:

Step One: Creating the decision matrix

Step Two: Calculating the normalized decision matrix using linear norm method

Step Three: Calculating the weight matrix with a weighting method

Step Four: determining the most suitable alternative $A^*$ using the following equation (Peng *et al.* 2016)

$$A^* = \{A_i | Max \sum_{j=1}^{n} n_{ij} w_j\} \tag{5}$$

In other words, in SAW, alternatives that have a greater sum of normalized weighted values will be selected.

### *3.1.3 VIKOR*

Introduced in 1984, VIKOR is a compromise method for prioritizing and ranking a number of alternatives based on criteria (Yunna *et al.* 2016). In this model, alternatives are evaluated and ranked by combination of values of criteria (Opricovic and Tzeng 2004).

The steps of VIKOR method are as follows (Opricovic and Tzeng 2004):

Step One: Creating the decision matrix

Step Two: Calculating the normalized decision matrix using linear norm method

Step Four: Calculating the weight matrix using weighting methods

Step Five: Determining the ideal positive and negative points for each criterion. Determining the best and worst values amongst all alternatives ($f^+$ and $f^-$). If the criteria are positive we will have [19]

$$f^+ = max\, x_{ij} \tag{6}$$

$$f^- = min\, x_{ij} \tag{7}$$

Step Six: Determining utility and regret values: utility $S_i$ is the relative distance of i-th alternative from the ideal point and regret value $R_i$ is the maximum amount of regret of i-th alternative for being far from the ideal point. These parameters are calculated using the following equations (Opricovic and Tzeng 2004)

$$S_i = \sum_{j=1}^{n} w_j \cdot \frac{f_j^+ - f_{ij}}{f_j^+ - f_j^-} \tag{8}$$

$$R_i = max \left[ w_j \cdot \frac{f_j^+ - f_{ij}}{f_j^+ - f_j^-} \right] \tag{9}$$

Step Seven: Calculating the VIKOR index $Q_i$ for each alternative. The VIKOR index for each alternative is calculated using the following formula (Yunna *et al.* 2016)

$$\begin{gathered} Q_i = v\left[\frac{S_i - S^+}{S^- - S^+}\right] + (1 - v)\left[\frac{R_i - R^+}{R^- - R^+}\right] \\ S^+ = MinS_i\, ;\, S^- = MaxS_i \\ R^+ = MinR_i\, ;\, R^- = MaxR_i \end{gathered} \tag{10}$$

#### *3.1.4 ELECTRE*

Introduced in the late 1980s, ELECTRE is a method of concordance type and is known as one of the best MCDM techniques. All steps of ELECTRE are based on a concordance set and a discordance set. The steps of this method are as follows (Milosz and Krzysztof 2016 and Fetanat and Khorasaninejad 2015):

Step One: Calculating normalized matrix using the vector norm method

Step Two: Calculating the weights of criteria

Step Three: forming the normalized weighted matrix

Step Four: Determining the concordance set and the discordance set (Milosz and Krzysztof 2016):

In this step, all alternatives are subjected to pairwise comparison. Criteria whose *k*-th alternative is superior to *l*-th alternative are put in the concordance set and the rest are put in the discordance set.

Step Five: forming the concordance matrix. The concordance matrix does not have any elements on the main diameter and its elements are obtained by summing the weights of concordance set. In other words, the sum of weights of criteria whose *k*-th alternative is superior to *l*-th alternative is put in element *kl* of the concordance matrix. Concordance matrix *I* is calculated using the following equation (Milosz and Krzysztof 2016)

$$I = \sum w_j \tag{11}$$

Step Six: calculating effective concordance matrix. In this step, the threshold $\bar{I}$ of the concordance matrix is calculated using the following equation (Fetanat and Khorasaninejad 2015)

$$\bar{I} = \sum_{l=1}^{m} \sum_{k=1}^{m} \frac{I_{k,l}}{m(m-1)} \tag{12}$$

*m*: the number of alternatives, $I_{k,l}$: elements of the concordance matrix

After calculating the threshold, those elements of the concordance matrix which are smaller than the threshold are turned to zero and other elements are turned to 1; these elements are put in a new matrix called “effective concordance matrix” $\overline{F_{kl}}$ (Fetanat and Khorasaninejad 2015).

$$\overline{F_{kl}} = \begin{cases} 1 & I_{kl} \geq \bar{I} \\ 0 & I_{kl} < \bar{I} \end{cases} \tag{13}$$

Step Seven: forming discordance matrix. To create the $NI_{kl}$ element of the discordance matrix, we calculate the ratio of the longest distance between *k* and *l* in criteria where *k* is smaller than *l*, and the longest distance between *k* and *l* in all criteria (Milosz and Krzysztof 2016).

$$NI_{kl} = \frac{max|v_{kj} - v_{lj}|, j \in D_{kl}}{max|v_{kj} - v_{lj}|, j \in all} \tag{14}$$

Step Eight: calculating the effective discordance matrix. In this step the threshold of discordance matrix is calculated using the following formula (Fetanat and Khorasaninejad 2015)

$$\overline{NI} = \sum_{l=1}^{m} \sum_{k=1}^{m} \frac{NI_{k,l}}{m(m-1)} \tag{15}$$

After calculating the threshold, those elements from the discordance matrix that had a value bigger than the threshold are tuned to zero and other elements are turned to one; then these elements are put in a new matrix called “effective discordance matrix” $\overline{G_{kl}}$ (Milosz and Krzysztof 2016).

$$\overline{G_{kl}} = \begin{cases} 1 & NI_{kl} \geq \overline{NI} \\ 0 & NI_{kl} < \overline{NI} \end{cases} \tag{16}$$

Step Nine: calculating the net effective matrix through the following equation (Fetanat and Khorasaninejad 2015)

$$H_{kl} = F_{kl} \cdot G_{kl} \tag{17}$$

In matrix $H_{kl}$, the sum of row figures equals the number of wins of an alternative and the sum of column figures equals the number of times an alternative has lost against other alternatives. In the ELECTRE method, the alternative that has a bigger loss-win difference has a higher rank.

### *3.1.5 Fuzzy TOPSIS*

In the classis TOPSIS, we determine the weight of the criteria and rank the alternatives using accurate and crisp values. In many problems however, there are some uncertainties that may affect the decision-making process (Sengul *et al.* 2015). In such cases, it is better to use the fuzzy decision-making approach (Cavallaro 2010). In the fuzzy TOPSIS, the elements of decision matrix or the weight of the criteria or both of them are evaluated by linguistic variables represented by fuzzy numbers (Sengul *et al.* 2015).

Step One: forming the decision matrix according to the number of alternatives and criteria, and evaluating all alternatives based on different criteria. The decision matrix is formed as below (Guo and Zhao 2015).

$$\widetilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{18}$$

Triangular fuzzy numbers are in the form $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ reflecting the association of alternative $i;i=1,2,...,n$ with criterion $j;j=1,2,...,n$ (Kannan *et al.* 2014).

Step Two: Determining the weight matrix of criteria. The importance weight of different criteria in decision-making process is defined as shown below, and in case of using triangular fuzzy numbers, the weight of each component of $w_j$ will be as follows (Sengul *et al.* 2015)

$$\widetilde{W} = [\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_n];\ \widetilde{w}_j = (\mathrm{w}_{j1}, \mathrm{w}_{j2}, \mathrm{w}_{j3}) \tag{19}$$

Step Three: Normalizing the fuzzy decision matrix

In the fuzzy decision matrix, $r_{ij}$s are fuzzy (triangular) numbers. In this step, criteria are normalized lineally to make them comparable. The elements of the normalized decision matrix for positive and negative criteria are calculated through the following equations (Sengul *et al.* 2015 and Guo and Zhao 2015)

$$r_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \tag{20}$$

$$r_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \tag{21}$$

In the end, the normalized fuzzy matrix is obtained as below: where *m* is the number of alternatives and *n* is the number of criteria (Milosz and Krzysztof 2016).

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1j} & \cdots & \tilde{r}_{1n} \\ \vdots & & \vdots & & \vdots \\ \tilde{r}_{i1} & \cdots & \tilde{r}_{ij} & \cdots & \tilde{r}_{in} \\ \vdots & & \vdots & & \vdots \\ \tilde{r}_{m1} & \cdots & \tilde{r}_{mj} & \cdots & \tilde{r}_{mn} \end{bmatrix} \tag{22}$$

Step Four: forming the normalized weighted fuzzy decision matrix.

Having the weight (importance) of each criterion, the weighted fuzzy decision matrix is obtained by multiplying the weight of criteria by the fuzzy normalized decision matrix (Sengul *et al.* 2015)

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_j \tag{23}$$

Step Five: determining the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS). Alternatives in $A^*$ and $A^-$ are better ideal alternatives and worse ideal alternatives respectively. FPIS and FNIS are defined as follows (Sengul *et al.* 2015)

$$A^* = \{\tilde{v}^*_1, \tilde{v}^*_2, \dots, \tilde{v}^*_n\} \tag{24}$$

$$A^- = \{\tilde{v}^-_1, \tilde{v}^-_2, \dots, \tilde{v}^-_n\} \tag{25}$$

$$\widetilde{V}_j^* = Max_i\{\tilde{v}_{ij3}\} \quad i = 1,2,\dots,m; j = 1,2,\dots,n \tag{26}$$

$$\widetilde{V}_j^- = Min_i\{\tilde{v}_{ij1}\} \quad i = 1,2,\dots,m; j = 1,2,\dots,n \tag{27}$$

$v_i^*$ is the best value of criterion *i* among all alternatives and $v_i^-$ is the worst value of the criterion among all alternative and is obtained from the equations below:

For triangular fuzzy numbers with positive and negative aspect, $\tilde{v}_{ij}$ is calculated as shown below (Guo and Zhao 2015)

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_j = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right).(w_{j1}, w_{j2}, w_{j3}) = \left(\frac{a_{ij}}{c_j^*}.w_{j1}, \frac{b_{ij}}{c_j^*}.w_{j2}, \frac{c_{ij}}{c_j^*}.w_{j3}\right) \tag{28}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij}.\tilde{w}_j = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right).(w_{j1}, w_{j2}, w_{j3}) = \left(\frac{a_j^-}{c_{ij}}.w_{j1}, \frac{a_j^-}{b_{ij}}.w_{j2}, \frac{a_j^-}{a_{ij}}.w_{j3}\right) \tag{29}$$

Step 6: the distance of each alternative from the positive ideal solution ($S_i^*$) and the distance of each alternative from the fuzzy anti-ideal solution ($S_i^-$) are calculated using the following equations (Kannan *et al.* 2014)

$$S_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right) \ , \ i = 1,2,\dots,m \tag{30}$$

$$S_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \ , \ i = 1,2,\dots,m \tag{31}$$

Step Seven: Calculating the closeness criterion. In this step the relative similarity or closeness an alternative to an ideal solution is obtained using the following equation (Guo and Zhao 2015, Kannan *et al*. 2014)

$$CC_i = \frac{S_i^-}{S_i^* + S_i^-} \tag{32}$$

Step Eight: ranking the alternatives in a descending order in terms of their closeness criterion.

#### *3.1.6 Ranking integration with simple averaging*

In this method, ranking of alternatives is finalized based on average of their ranks in different MCDM methods. In this method, we calculated the arithmetic mean of the obtained ranks in different MCDM methods and form the final ranking based on these averages.

#### *3.1.7 Ranking integration with Borda count*

In this method, ranking is conducted based on pairwise comparison of alternatives and the number of times that an alternative has won in decision making methods. In this method, we form a pairwise comparison matrix between the alternatives (Phelipe *et al*. 2016). For example, when majority of MCDM methods prefer alternative $A_i; i=1,2,\dots,m$ over alternative $A_j; j=1,2,\dots,m$ we show this preference in the pairwise comparison matrix with *M*, and use *X* if the opposite is true. Thus, *M* means that row item is more preferable than column item and *X* shows that column item is more preferable than row item. This pairwise comparison is performed separately for every alternative. In this method, the number of comparisons is equal to $m(m\text{-}1)/2$ where *m* is the number of alternatives. The prioritization criterion in this method is the number of wins of each alternative, *M*.

#### *3.1.8 Ranking integration with Copland's method*

This method is similar to that of Borda's with the difference that the number of losses of each alternative is also considered in prioritization (Phelipe *et al*. 2016). In this method, once the pairwise comparison matrix is formed, the number of losses $\Sigma R$ of each alternative is subtracted from the number of wins $\Sigma W$ of that alternative, and the results are used to form the final ranking.

#### *3.1.9 Integration phase*

In this phase, we use the three above ranking integration methods to achieve a consensus by forming a Partially Ordered Set (Poset). A Poset is a set in which sorting concept is formulized using the HASSE diagram.

### *3.2 Site location criteria*

Utilization of hydrogen production capacity through environmentally friendly operations must be in accordance with regional, national, and environmental regulations as well as operational constraints. Table 2 shows the spatial constraints regarding this issue including provincial and

Table 2 Restrictions regarding site selection

| Objective | Constraint |
|---|---|
| Maintaining the safety of residents | 500 m distance from residential areas |
| Protecting the natural resources | 250 m distance from water resources, rivers |
| Infrastructural limitations | 250 m distance from road network<br>250 m distance from power grid<br>500 m distance from railways |

Table 3 Decision criteria

| NO | Criteria | Effect |
|---|---|---|
| 1 | Solar energy potential | positive |
| 2 | Wind energy potential | positive |
| 3 | Frequency of dust phenomenon | negative |
| 4 | Air temperature | negative |
| 5 | Distance from main road | negative |
| 6 | Land price | negative |
| 7 | Natural disasters | negative |
| 8 | Distribution of population | positive |
| 9 | Altitude | positive |
| 10 | The ability to expand | positive |

municipal boundaries, marches, airports, ports, urban and industrial areas, special areas, protected areas, high-voltage electricity transmission lines, and road and transportation network.

Criteria defined in Table 3 include: solar energy potential, wind energy potential, dust, temperature, distance from roads, cost of land, likelihood of natural disasters, population, elevation and expandability for other renewable energy sources. Solar energy potential was calculated using the Angstrom formula, for which dimensionless values were obtained from previous studies. Angstrom formula for solar energy potential requires data on sunshine hours, latitude, sun declination angle and Julian date. The values of these parameters were calculated for all 25 alternatives and their annual radiation potential graphs were plotted. Wind energy potential was calculated using the Weibull distribution function. This calculation was carried out for all 25 alternatives by using data on wind speed, air pressure and temperature.

Depending on their effects, criteria of multi-criteria problems can be divided into two categories: positive and negative. Positive criteria are those that have a positive impact on the decision-making process and need to be maximized, while negative criteria are that should be minimized (Sengul *et al.* 2015). Fig. 3(a)-3(h) shows the decision criteria on layers of geographic information maps. The required geographic information maps were obtained from the software ArcGIS.

#### *3.2.1 Solar energy potential*

The amount of solar radiation that can be harvested by photovoltaic systems to produce electricity is a critical criterion in determining the suitable location for renewable hydrogen production (Phelipe *et al.* 2016). The magnitude and quality of solar energy received on the earth surface can be influenced by meteorological parameters (Najafi *et al*. 2015). Meteorological parameters associated with solar energy potential include temperature, precipitation, humidity, sunshine hours, cloudiness and latitude. Monthly average daily solar radiation received by a horizontal surface can be estimated with Angstrom-Prescott model. Angstrom formula has been defined as follows (Green *et al.* 2015)

$$\frac{\bar{H}}{\bar{H}_0} = a + b\left(\frac{\bar{n}}{\bar{N}}\right) \tag{33}$$

Where $H_0$ must be obtained directly from the following equation (Dumas *et al.* 2011)

$$H_0 = \frac{24 \times 3.6 \times I_{sc}}{\pi}\left[1 + 0.033\cos\left(360\frac{\bar{D}}{365}\right)\right]\cos\varphi\cos\delta\sin\omega + \omega\sin\varphi\sin\delta \tag{34}$$

$\delta$ is the sun declination angle, which must be calculated by the following equation (Esteves *et al.* 2015)

$$\delta = 23.45\sin\left(360\frac{248+\bar{D}}{365}\right) \tag{35}$$

$\omega$ is the sunset hour angle, which is calculated as follows (www.geoliving.co.uk)

$$\omega = \cos^{-1}(-\tan\varphi\tan\delta) \tag{36}$$

Lastly, day length is obtained from the following equation (www.geoliving.co.uk)

$$\bar{N} = \left(\frac{2}{15}\right)\omega \tag{37}$$

### 3.2.2 Wind energy potential

Wind speed has a random nature, and to model its behavior a suitable probability density function must be selected (www.thewindpower.net). This issue has been addressed by many studies and many different probability density functions have been provided. In this study, we used the Weibull probability distribution function, which is largely known as a top-quality function for representing the probability density of a random variable such as wind speed (Mostafaeipour and Abarghooei 2008).

Wind power potential must be calculated using the long-term data pertaining to the area under study. In Iran, meteorological organization records data at a height of 10 meters. But most of the wind turbines are 50 meters high (Cancino-Solórzano *et al.* 2010), so the wind speed at this height must be calculated by a simple formula commonly known as the one-seventh-power rule. This formula is expressed as follows (www.thewindpower.net).

$$v_2 = v_1\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{38}$$

In this study, the coefficient of this formula was assumed to be 0.14 (www.thewindpower.net). At heights of less than 100 meters, changes in temperature and air pressure are very slight. So, to calculate the wind energy potential at the desired height, we only need to calculate the wind speed at that height. Weibull distribution function can be expressed as follows (Aryanpur and Shafiei 2015)

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)e^{-\left(\frac{v}{c}\right)^k} \tag{39}$$

*C* is a dimensionless constant and k is the shape parameter, which can be calculated as follows (www.thewindpower.net)

$$c = \frac{v}{\Gamma\left(1+\frac{1}{k}\right)} \tag{40}$$

$$k = 0.83\ v^{0.5} \tag{41}$$

Γ is the gamma function and is in the form of follows equation (Cancino-Solórzano *et al.* 2010)

$$\Gamma(x) = \int_0^\infty e^{-u}u^{x-1}\,du \tag{42}$$

The general equation of power is as follows (Aryanpur and Shafiei 2015)

$$p(v) = \frac{1}{2}\rho a v^3 \tag{43}$$

Where P is the density of the ambient air can be calculated as follows (Cancino-Solórzano *et al.* 2010)

$$\rho = \frac{\bar{P}}{R_d\,\bar{T}} \tag{44}$$

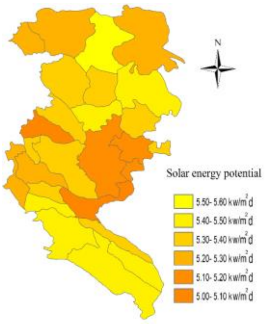
Finally, wind power for area A of turbine blade is obtained from the following equation (www.thewindpower.net)

$$\frac{P}{A} = \int_0^\infty \frac{1}{2}\rho v^3 f(v)\,dv = \frac{1}{2}\rho c^3\left(1+\frac{3}{K}\right) \tag{45}$$

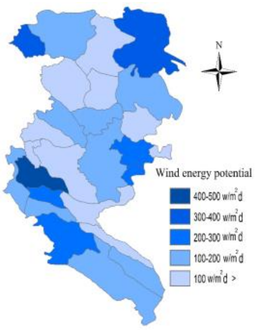
### 3.3 Electrolyzer

The electricity produced by renewable energy systems will be sent to the electrolyzer to power the water electrolysis process (Esteves *et al.* 2015). There are a variety of water electrolysis methods with different technologies. This study assumes that system will use a proton exchange membrane electrolyzer. This method has a high efficiency and long-life cycle and is suitable for renewable energy systems like wind and solar, where electricity production is variable. The produced hydrogen also needs to be stored (Aryanpur and Shafiei 2015). The hydrogen produced by the mentioned method will have a pressure of 1 ½bar, which eliminates the need for compressors (Huang *et al*. 2016). Thus, outlet of the electrolyzer is directly connected to the storage tanks. Proton exchange membrane electrolyzer has an energy consumption of 52.5 kWh per kilogram (Sigal *et al*. 2014). The mass of hydrogen produced with solar and wind energy is calculated as follows (Komiyama *et al*. 2015, Kabak and Dağdeviren 2014 and www.uea.ac.uk)

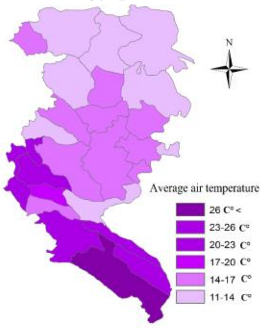
$$M_{H_2} = \frac{E_{H_2}}{LHV_{H_2}} = \frac{\eta_1.\eta_2.E_{RE}}{LHV_{H_2}} \tag{46}$$



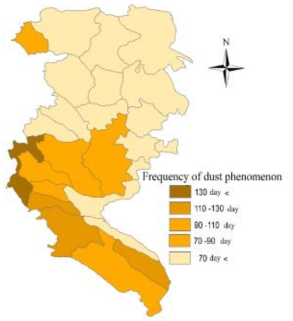

(a) Solar energy potential of area



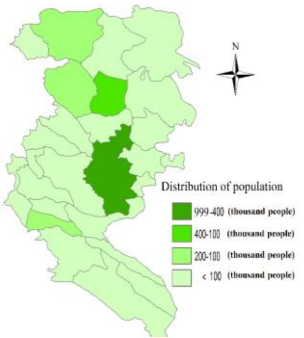

(b)Wind energy potential of area



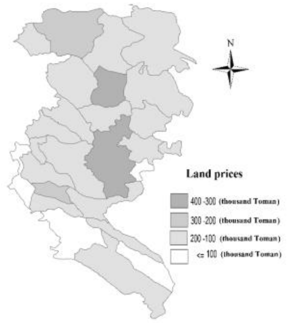

(c) Air temperature in the area



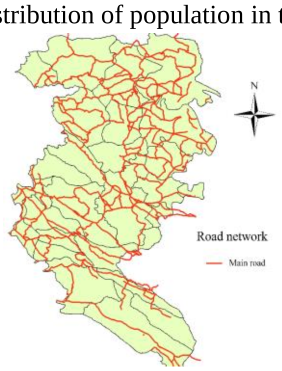

(d) Frequency of dust phenomenon in the area



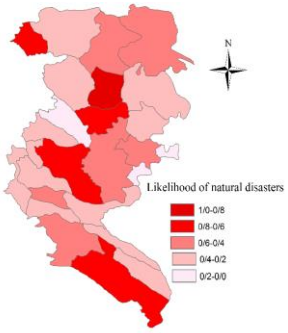

(e) Distribution of population in the area




(f) land price in the area




(g) Road network in the area




(h) Likelihood of natural disasters over 25-year period (www.mrud.ir)

Fig. 3 Site location criteria

## 4. Results of MCDM methods

Table 4 presents the rankings obtained with TOPSIS, VIKOR, SAW, ELECTRE, fuzzy TOPSIS and three hybrid methods based on Borda count, Copeland’s method, and simple averaging of ranks. According to the results, all methods have put Sanandaj in the first place and most methods have put Kermanshah in the second place, while Ilam, Qorveh, and Saghez have been put in the third place of partially ordered set. Given the differences in the used MCDM method and smoothing approaches, lower ranks differ with the method. To obtain a more reliable solution, the hybrid ranking methods were employed.

Rankings were integrated by the use of partially ordered sets. In the partially ordered set, alternative is better than j only if all methods report such relationship, otherwise no relationship can be defined. Table 5 shows the rankings of cities based on Borda count, Copeland’s method, and simple averaging of ranks. As can be seen, all methods have put Sanandaj in the first place and most methods have put Kermanshah in the second place, while Ilam, Qorveh, and Saghez have been put in the third place of partially ordered set. The lowest ranks have been assigned to Darreshahr, Dehloran, and QasrShirin.

Table 4 Results of MCDM methods

| Sites | Ranked by ELECTRE | Ranked by VIKOR | Ranked by SAW | Ranked by TOPSIS | Ranked by fuzzy TOPSIS | Ranked by Borda | Ranked by average ratings ranking | Ranked by Copland |
|---|---|---|---|---|---|---|---|---|
| Abdanan | 18 | 24 | 5 | 24 | 21 | 20 | 20 | 20 |
| Baneh | 6 | 7 | 7 | 11 | 5 | 7 | 6 | 7 |
| Bijar | 9 | 9 | 12 | 6 | 7 | 8 | 8 | 8 |
| Darrehshahr | 24 | 25 | 4 | 25 | 25 | 23 | 23 | 23 |
| Dehloran | 25 | 22 | 13 | 20 | 23 | 21 | 24 | 21 |
| Divandarreh | 20 | 15 | 22 | 13 | 15 | 14 | 18 | 14 |
| Eevan | 10 | 16 | 25 | 10 | 13 | 10 | 14 | 10 |
| Eslamabadgharb | 8 | 11 | 8 | 19 | 12 | 10 | 10 | 10 |
| Gasrshirin | 21 | 23 | 15 | 22 | 24 | 22 | 25 | 22 |
| Ghorveh | 2 | 5 | 17 | 5 | 3 | 3 | 5 | 3 |
| Gilangharb | 17 | 21 | 3 | 23 | 6 | 17 | 13 | 17 |
| Harsin | 7 | 6 | 18 | 7 | 4 | 6 | 7 | 6 |
| Ilam | 5 | 3 | 6 | 3 | 8 | 4 | 3 | 4 |
| Kamyaran | 12 | 12 | 16 | 8 | 11 | 9 | 11 | 9 |
| Kangavar | 13 | 14 | 21 | 18 | 17 | 16 | 17 | 16 |
| Kermanshah | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Marivan | 11 | 8 | 10 | 9 | 18 | 11 | 9 | 11 |
| Mehran | 23 | 19 | 19 | 15 | 20 | 18 | 21 | 18 |
| Paveh | 15 | 13 | 24 | 14 | 14 | 12 | 15 | 12 |
| Ravansar | 19 | 17 | 23 | 16 | 16 | 16 | 19 | 16 |
| Saghez | 3 | 4 | 9 | 4 | 9 | 5 | 4 | 5 |

Table 4 Continued

| Sites | Ranked by ELECTRE | Ranked by VIKOR | Ranked by SAW | Ranked by TOPSIS | Ranked by fuzzy TOPSIS | Ranked by Borda | Ranked by average ratings ranking | Ranked by Copland |
|---|---|---|---|---|---|---|---|---|
| Sahneh | 14 | 18 | 20 | 12 | 19 | 15 | 16 | 15 |
| Sanandej | 4 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Sarpolzahab | 22 | 20 | 14 | 21 | 22 | 19 | 22 | 19 |
| Songhor | 16 | 10 | 11 | 17 | 10 | 13 | 12 | 13 |

Table 5 Ranking obtained with partially ordered set

| No | Sites | Ranking |
|---|---|---|
| 1 | Kermanshah | Rank1 |
| 2 | Sanandaj | Rank2 |
| 3 | Ilam, Ghorveh, Saghez | Rank3 |
| 4 | Harsin, Baneh | Rank4 |
| 5 | Bijar | Rank5 |
| 6 | Eslamabadgharb, Eavan, Marivan, kamyaran | Rank6 |
| 7 | Pavaeh, Saghez | Rank7 |
| 8 | Divandarreh, Sahneh, Gilangharb | Rank8 |
| 9 | Ravansar, Kangavar | Rank9 |
| 10 | Mehran, Abdanan | Rank10 |
| 11 | Sarpolzahab | Rank11 |
| 12 | Darrehshahr, Dehloran, Gasrshirin | Rank12 |

Table 6 Estimated potential for renewable hydrogen production in the studied cities

| Sites | Available wind energy ($kWh/m^2.yr$) | $Mh_2$-wind ($kg/m^2.yr$) | Available solar energy ($kWh/m^2.yr$) | $Mh_2$- solar ($kg/m^2.yr$) | $Mh_2$-wind and solar ($kg/m^2.yr$) |
|---|---|---|---|---|---|
| Abdanan | 1297.739 | 23.36164 | 1941.877 | 32.6268 | 55.98845 |
| Baneh | 3137.513 | 56.48088 | 1877.614 | 31.54707 | 88.02795 |
| Bijar | 2711.41 | 48.81026 | 1900.494 | 31.93149 | 80.74175 |
| Darrehshahr | 542.6667 | 9.768978 | 1933.063 | 32.4787 | 42.24768 |
| Dehloran | 1113.152 | 20.03875 | 1953.797 | 32.82707 | 52.86582 |
| Divandarreh | 925.3241 | 16.6575 | 2030.145 | 34.10984 | 50.76734 |
| Eevan | 2148.865 | 38.68344 | 1936.851 | 32.54235 | 71.22579 |
| Eslamabadgharb | 683.3513 | 12.30155 | 1932.992 | 32.47752 | 44.77907 |
| Gasrshirin | 991.0109 | 17.83998 | 1876.536 | 31.52895 | 49.36893 |
| Ghorveh | 1491.55 | 26.85058 | 1960.004 | 32.93135 | 59.78193 |
| Gilangharb | 4198.137 | 75.57403 | 1901.61 | 31.95024 | 107.5243 |
| Harsin | 1801.01 | 32.42142 | 1859.669 | 31.24557 | 63.66699 |

Table 6 Continued

| Sites | Available wind energy (kWh/m$^2$.yr) | $Mh_2$-wind (kg/m$^2$.yr) | Available solar energy (kWh/m$^2$.yr) | $Mh_2$- solar (kg/m$^2$.yr) | $Mh_2$-wind and solar (kg/m$^2$.yr) |
|---|---|---|---|---|---|
| Ilam | 922.1531 | 16.60042 | 1941.656 | 32.62308 | 49.22349 |
| Kamyaran | 1213.483 | 21.84488 | 1961.333 | 32.95368 | 54.79856 |
| Kangavar | 523.7284 | 9.428055 | 1928.843 | 32.40781 | 41.83586 |
| Kermanshah | 982.0512 | 17.67869 | 1852.023 | 31.11709 | 48.79578 |
| Marivan | 405.9789 | 7.308351 | 1903.36 | 31.97964 | 39.28799 |
| Mehran | 2488.059 | 44.78954 | 1944.675 | 32.6738 | 77.46335 |
| Paveh | 907.7825 | 16.34172 | 1911.784 | 32.12119 | 48.4629 |
| Ravansar | 974.5584 | 17.54381 | 1918.798 | 32.23903 | 49.78284 |
| Saghez | 977.1849 | 17.59109 | 1898.758 | 31.90233 | 49.49342 |
| Sahneh | 898.9897 | 16.18343 | 1863.003 | 31.30157 | 47.48501 |
| Sanandej | 574.3067 | 10.33855 | 1929.816 | 32.42414 | 42.7627 |
| Sarpolzahab | 630.3398 | 11.34725 | 1916.98 | 32.20848 | 43.55574 |
| Songhor | 1906.769 | 34.32528 | 1935.494 | 32.51955 | 66.84482 |

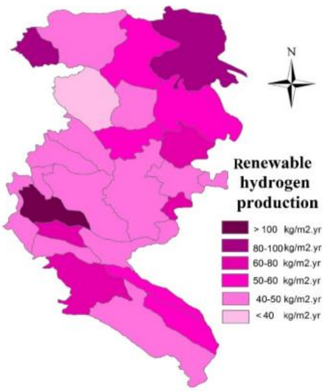



Fig. 4 Renewable hydrogen production potential in the study area

### *4.1 Electrolysis hydrogen production potential*

The electricity produced by renewable energy systems will ultimately power the water electrolysis process in the electrolyzer. In this paper, we assumed a proton exchange membrane electrolyzer with efficiency factor of 0.75 that can produce one kilogram of hydrogen gas by consuming 52.5 kilowatt-hours of energy. Renewable energy obtained from wind and solar energy sources were converted to the unit kWh/ (m$^2$ year). Note that the term m$^2$ in the expression of solar energy refers to one square meter in the horizontal plane, and the term m$^2$ in the expression of wind energy refers to one square meter of turbine blade installed at a height of 50 meters. Table 6 shows the potential for renewable hydrogen production in the studied cities on an annual basis.

Gilangharb with annual hydrogen production capacity of 107.52 kg based on energy of one square meter of solar cell and one square meter of turbine blade installed at the height of 50 m, has the highest renewable hydrogen production capacity among the studied cities. Fig. 4 shows the graphical information map of renewable hydrogen production potential (plotted with ArcGIS).

## 5. Conclusions

Energy is an essential commodity for economic, industrial and scientific development of nations, and procurement of reliable and stable energy supplies is one of the greatest challenges of the present age. Today, the bulk of global energy demand is met by fossil fuel sources such as oil, gas and coal. However, the use of modern technologies for, for example, renewable hydrogen production can eliminate some of the limitations in regard to the use of renewable energy sources. In this study, 25 cities in three of Iran's western province Kermanshah, Ilam, Kurdistan were evaluated in terms of their suitability for renewable hydrogen production. In the first step, research criteria were obtained from the literature by library research and assessment of regional parameters. The result of conducted studies suggested that the efficiency of renewable hydrogen production is governed by climatic, geographic, economic, social, and technical factors including solar energy potential, wind energy potential, frequency of dust phenomenon, temperature, distance from the main roads, land price, likelihood of natural disasters such as hurricanes, floods and earthquakes, population, elevation and expandability for other renewable energy sources. After determining the effective criteria, 25 available alternatives were ranked with TOPSIS. Weights of criteria were determined using the Shannon entropy method. The results of TOPSIS were then validated with SAW, VIKOR, ELECTRE, and fuzzy TOPSIS. Validation results indicated that Kermanshah is the top choice for producing renewable hydrogen. Since the rankings obtained with different MCDM methods had slight differences, they were integrated by applying Borda count and Copeland's method and also by simple averaging. In the end, Poset-based (partially ordered set) ranking was used to integrate and finalize the results. In the final results, Kermanshah, which gained the top rank in all MCDM methods, was also recognized in the Poset-based ranking as the top choice. Evaluation of renewable hydrogen production capacity of cities showed that Gilangharb has the highest capacity among the studied cities.

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