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Optimal location planning to install wind turbines for hydrogen production: A case study

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Abstract. This study aims to evaluate and prioritize ten different sites in Iran's Khorasan provinces for the construction of wind farm. After studying the geography of the sites, nine criteria; including wind power, topography, wind direction, population, distance from power grid, level of air pollution, land cost per square meter, rate of natural disasters, and distance from road network-are selected for the analysis. Prioritization is performed using data envelopment analysis (DEA). The developed DEA model is validated through value engineering based on the results of brainstorming sessions. The results show that the order of priority of ten assessed candidate sites for installing wind turbines is Khaf, Afriz, Ghadamgah, Fadashk, Sarakhs, Bojnoord, Nehbandan, Esfarayen, Davarzan, and Roudab. Additionally, the outcomes extracted from the value engineering method identify the city of Khaf as the best candidate site. Six different wind turbines (7.5 to 5,000 kW) are considered in this location to generate electricity. Regarding an approach to produce and store hydrogen from wind farm installed in the location, the AREVA M5000 wind turbine can produce approximately 337 ton-H_2 over a year. It is an enormous amount that can be used in transportation and other industries.

Keywords: hydrogen production; wind turbine; data envelopment analysis (DEA); rioritization; Khorasan provinces

1. Introduction

The well-established and growing use of renewable energy in developed countries has encouraged significant efforts all over the world to make more and better use of this energy (Qolipour *et al.* 2016). Iran, like many other countries, has significant potential for production of renewable energies especially wind power, as many windy parts of this country including the coasts of Oman Sea and Khuzestan province, the eastern region, the Persian Gulf Islands, Manjil,

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Rafsanjan, Ardebil and Bijar, are suitable for production of electricity from these types of energy (Gandomkar 2010). The use of wind energy has seen a considerable global growth and support thanks to its major advantages (Bahrami and Abbaszadeh 2010, Carnevale *et al.* 2016), and mainly its significant contribution to reduction of greenhouse gas emissions (Aydin *et al.* 2010). Research has shown that 1 kWh of electricity generated by wind turbines prevents the emission of about one kilogram of CO_2 by fossil power plants (Sana 2010). The first step in the use of wind energy is to convert it into a globally usable energy carrier, that is, electricity. The first requirement of this step is the proper selection of a site for the construction of wind turbines. Thus, site location and prioritization are of particular importance for establishing a wind power system (Chowdhury *et al.* 2013). This field has been the subject of considerable research; for example: Heydar Aras *et al.* (2014) determined the proper location of a wind farm by analytic hierarchy process (AHP). Tigo *et al.* (2010) developed an integrated framework for the assessment of wind farm candidate sites with AHP and Geographic Information System (GIS). Today, the entire world is on a mission to develop and promote renewable energy technologies as replacement of fossil fuels and a solution for their high pollution (Brunner *et al.* 2011). One prime example of clean fuel is hydrogen, which can be produced using fossil fuels, water electrolysis, thermochemical reactions, biomass energy, and photovoltaic systems and be consumed in fuel cells etc. to generate energy (Huang *et al.* 2016). Saeidi *et al.* (2016) implemented DEA for optimum production of palm oil which the results were satisfactory. This field has also been extensively researched; for example: Zini and Rosa (2014) and Chavez Ramirez *et al.* (2013) developed a hydrogen energy storage system and simulated the proposed system using real data from photovoltaic plants in Central Italy and Mexico. Their results showed that in the future, this system could be a good solution to overcome the production instability of renewable energies. Saryas Mena *et al.* (2015) introduced and compared four different electrolyzers for producing hydrogen from wind power. They performed a simulation in MATLAB environment by assuming a variable wind speed and reported that all assessed electrolyzers have acceptable compatibility. Iche Hamana *et al.* (2009) evaluated the feasibility of producing hydrogen from 5 kW electrolyzer powered by 10 wind turbines installed in Qardaya, Algeria. They concluded that the height of wind turbine rotor is a key factor in increasing the hydrogen production potential of the assessed system. Rodriguez *et al.* (2010) analyzed the potential of producing hydrogen from wind energy in Argentina. The aim of this study was to provide transport by hydrogen produced using the power of wind farms in the Córdoba Province. Kostanda *et al.* (2013) provided a dynamic model and energy management strategies for a solar-hydrogen hybrid system. Chavez-Ramirez *et al.* (2013) provided a model for wind-solar-hydrogen hybrid power plants for remote areas using artificial intelligence. Valdez *et al.* (2013) simulated the operations of a wind farm producing hydrogen. Petrakopolo *et al.* (2016) made an analysis and dynamic simulation to achieve energy saving through hydrogen production in a wind-solar hybrid power plant. Ozdan and Tari (2016) performed an economic analysis on a solar-hydrogen hybrid system in Turkey. Mostafaeipour *et al.* (2016a) evaluated the potential of hydrogen production using wind energy in central Iran. There are many works in literature that show positive view of using renewable energies (Alavi *et al.* 2016c, Mostafaeipour and Abesi 2010, Mostafaeipour *et al.* 2014, Mostafaeipour *et al*. 2016b, Qolipour *et al.* 2016, Shamshirband *et al*. 2015, Shamshirband *et al.* 2016).

The main objective of this study is to evaluate and prioritize 10 regions of Khorasan Province (Iran) including Esfarāyen, Bojnoord, Davarzan, Sarakhs, Ghadamgah, Khaf, Roudab, AFriz, Fadashk, and Nehbandan for the construction of a wind farm supplemented with a hydrogen production system. This prioritization will be carried out using Data Envelopment Analysis (DEA) based on 9 criteria: wind power, wind direction, topography, population, distance from power grid, level of air pollution, land cost per square meter, rate of natural disasters, and distance from road network.

2. Geographic characteristic

Iran is a vast country situated in the Middle East with an area of 1,648,195 km^2. Iran enjoys highly diverse climatic conditions with the high temperature difference between hottest and coldest regions of the country. Iran is subdivided into 31 provinces. Khorasan province was the biggest province of Iran. It was divided in 2004 to three provinces named as North Khorasan, Razavi Khorasan and South Khorasan. Both North Khorasan and Razavi Khorasan provinces are located in the north-east part of Iran. The North Khorasan province with an area of 28,179 km^2 is located between 36°42’ N and 38°14’ N and also between 56°30’ E and 58°30’ E. Also, the Razavi Khorasan province which has the total area of 118,854 km^2 is situated between 33°52’ N

Table 1 Geographical information of the considered locations from Khorasan provinces (Arabi 2015)

Location	Province	Latitude (°N)	Longitude (°E)
Esfaraen	North Khorasan	37.08	57.50
Bojnoord	North Khorasan	37.47	57.32
Davarzan	Razavi Khorasan	36.26	56.81
Sarakhs	Razavi Khorasan	36.21	61.14
Ghadamgah	Razavi Khorasan	36.05	59.00
Khaf	Razavi Khorasan	34.58	60.16
Rudab	Razavi Khorasan	35.61	57.30
Afriz	Razavi Khorasan	34.44	58.96
Fadashk	South Khorasan	32.78	58.78
Nehbandan	South Khorasan	31.56	60.07

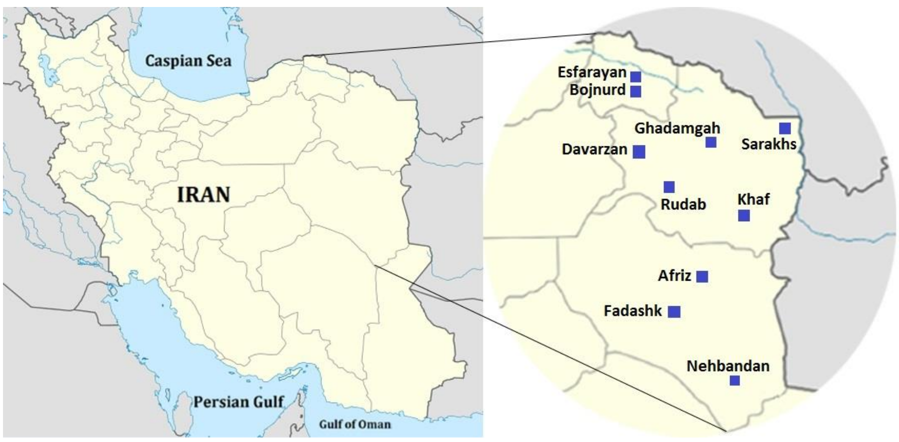

Fig. 1 Map of Khorasan province including case studies

and 37°42’ N and also between 56°19’ E and 61°16’ E.Moreover, South Khorasan province as the third largest province of Iran is located in the east part of the country. South Khorasan province with an area of 151,193 km^2 is located in the latitude range of 30°31’ N to 34°53’ N and in the longitude range of 57°30’ E and 60°57’ E (Arabi 2015). For this research work, ten different locations distributed in different parts of three Khorasan provinces have been considered as the case studies. The required information for the selected locations including their geographical characteristics is provided in Table 1.

The map of Iran including the location of the case studies are illustrated in Fig. 1.

3. Data envelopment analysis (DEA)

In a method proposed by Charnes, Cooper & Rhodes (CCR), they explained data envelopment aalysis (DEA) as a practical programming model to analyze the observed data such as the production function or the efficient production possibility frontier which are the foundations of the modern economy (Charnes *et al.* 1978).

Data envelopment analysis (DEA) is a nonparametric technique for measuring and evaluating the relative efficiency of the series of entities (organizations) with certain inputs and outputs (Kao *et al.* 2000). In other words, it has been created as a method to calculate the relative efficiency of decision-making units (DMUs) that use similar multiple sources to generate the same output. This approach consists of several mathematical models that all have the element of envelopment. The objective of DEA is to evaluate the relative efficiency of multiple decision-making units using multiple set of data regarding inputs and outputs. The term relative is essential in the definition of DEA, because a DEA can simultaneously be efficient with a particular set of DMUs and inefficient with another set of DMUs. The starting point for the use of DEA is to create a ratio of the sum of weighted outputs to the sum of weighted inputs for each DEA.

3.1 BCC model

This model was introduced by Banker, Charnz & Cooper (BCC) in 1984 (Charnes *et al.* 1984). It is similar to CCR model, except that the BCC model allows variable (increasing, decreasing, constant) returns to scale. That is why the restrictions should be convex. Banker, Charnz & Cooper have stated the following description of BCC model (Ramazankhani *et al.* 2016, Arabi 2015)

$$\begin{aligned} & Max\,\varphi \\ & s.t: X\lambda \le x_0 \\ & Y\lambda \ge \varphi y_0 \\ & \sum \lambda = 1 \\ & \lambda \ge 0 \\ & \theta : unrestricted\ in\ sign \end{aligned} \tag{23}$$

1. The multiplicative form of output oriented BCC will be as follows (Arabi 2015)

$$\begin{aligned} & Min\, z = v^t x_0 - v_0 \\ & s.t: u^t y_0 \quad = 1 \\ & \quad v^t X - u^t Y - v_0 e \leq 0 \\ & \quad u \geq 0, v \geq 0 \\ & \quad \theta : unrestricted\ in\ sign \end{aligned} \tag{24}$$

2. The fractional form of BCC will be as follows (Arabi 2015)

$$\begin{aligned} & Min \frac{v^t x_0 - v_0}{u^t y_0} \\ & s.t: \frac{v^t x_j - v_0}{u^t y_j} \quad \geq 1 \\ & \quad v \geq 0, u \geq 0 \\ & \quad \theta : unrestricted\ in\ sign \end{aligned} \tag{25}$$

3.2 Input oriented BCC model

$$\begin{aligned} & Min\, \theta \\ & s.t: \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{i0} \quad , i = 1, 2, ..., m \\ & \quad \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{r0} \quad , r = 1, 2, ..., s \\ & \quad \sum_{j=1}^{n} \lambda_j = 1 \quad , j = 1, 2, ..., n \\ & \quad \lambda_j \geq 0 \end{aligned} \tag{1}$$

This model is similar to CCR envelopment model except that it also includes $\sum_{j=1}^{n} \lambda_j = 1$ constraint. Its dual envelopment form is as follows (Ramazankhani *et al.* 2016, Rezaei-Shouroki *et al.* 2017)

$$\begin{aligned} & Max\, u^t y_0 - u_0 \\ & s.t: v^t x_0 \quad = 1 \\ & \quad u^t y_j - v^t x_j - u_0 \leq 0 \\ & \quad u \geq 0, v \geq 0 \quad , j = 1, 2, ..., n \end{aligned} \tag{2}$$

This is the multiplicative form of input-oriented BCC model. Given that $v^t x_0 = 1$, objective function of the above model will be as follows. This is the fractional form of input-oriented BCC model.

$$Max \frac{u^t y_0 - u_0}{v^t x_0}$$
$$s.t: \frac{u^t y_j - u_0}{v^t x_j} \leq 1 \tag{3}$$
$$v \geq 0, u \geq 0$$

u_0 is unrestricted in sign (Arabi 2015):

1. If (u_0>0) then the returns to scale will be decreasing.
2. If (u_0=0) then the returns to scale will be constant.
3. If (u_0<0) then the returns to scale will be increasing.

In the same study, they have stated that the above model is equivalent to Shephard's distance function which is expressed as follows

$$Max\, h'(X,Y) = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0} + v_0}$$
$$s.t: \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{i0} + v_0} \leq 1 \tag{4}$$
$$u_r, v_i \geq 0$$
$$\theta : unrestricted\ in\ sign$$

In this model, v_0 represents the returns to scale (Arabi 2015, Charnes *et al.* 1984)

1. In BCC model, DMU_0 is Pareto-efficient, when θ^*=1 and all slacks in all optimal solutions are zero.

2. In BCC model, DMU_0 is weakly-efficient, when in input oriented form (θ^*=1) and there is at least one positive slack in one optimum solution, or when in output oriented form (φ^*=1) and there is at least one positive slack in one optimum solution.

3. In BCC model, DMU_0 is inefficient, when production possibility set E_0 is as follows:

E_0= {j | $(\lambda_j^* \succ 0)$ in at least one optimum solution}

4. If BCC envelopment model has multiple efficiencies, by selecting one of them, the projection of inefficient DMU_0 which is called improved DMU will be as follows (Arabi 2015)

$$\begin{Bmatrix} \hat{x}_0 = \theta_B^* x_0 - s^{*-} \\ \hat{y}_0 = y_0 + s^{*+} \end{Bmatrix} \tag{5}$$

1. In BCC model, improved unit means that it is Pareto efficient.
2. A unit is improved when it has the lowest value at K^th^ input compared with other units, or when it has the highest value at l^th^ output compared with other units.
3. Input oriented BCC envelopment model is robust against the transfer of outputs. This means that if $\begin{matrix} y_{rj} \to y_{rj} + \beta_r \\ r = 1, 2, \ldots, s \\ i = 1, 2, \ldots, m \end{matrix}$ then the optimum solution does not change.
4. Output oriented BCC envelopment model is robust against the transfer of inputs.

3.3 Output oriented BCC model

1. The envelopment forms of output oriented BCC will be as follows (Mirjalili *et al.* 2010)

$$\begin{aligned} & Max\,\varphi \\ & s.t: X\lambda \le x_0 \\ & \quad Y\lambda \ge \varphi y_0 \\ & \quad \sum \lambda = 1 \\ & \quad \lambda \ge 0 \\ & \quad \theta : unrestricted\ in\ sign \end{aligned} \tag{6}$$

2. The multiplicative form of output oriented BCC will be as follows (Mirjalili *et al.* 2010)

$$\begin{aligned} & Min\, z = v^t x_0 - v_0 \\ & s.t: u^t y_0 \quad = 1 \\ & \quad v^t X - u^t Y - v_0 e \le 0 \\ & \quad u \ge 0, v \ge 0 \\ & \quad \theta : unrestricted\ in\ sign \end{aligned} \tag{7}$$

3. The fractional form of BCC will be as follows (Arabi 2015)

$$\begin{aligned} & Min \frac{v^t x_0 - v_0}{u^t y_0} \\ & s.t: \frac{v^t x_j - v_0}{u^t y_j} \quad \ge 1 \\ & \quad v \ge 0, u \ge 0 \\ & \quad \theta : unrestricted\ in\ sign \end{aligned} \tag{8}$$

3.4 Output oriented CCR

If a unit with the input of x_0 produce the output of [φy_0] and (φ>1), then it is obvious that the DMU with vector (x_0, φy_0) exceeds the DMU of (x_0, y_0) (Arabi 2015)

$$\begin{aligned} & Max\varphi \\ & s.t: \quad \sum_{j=1}^{n} \lambda_j x_j \le x_0 \\ & \sum_{j=1}^{n} \lambda_j y_j \ge \varphi y_0 \\ & \lambda_j \ge 0 \quad ,(j=1,2,...,n) \end{aligned} \tag{9}$$

1. This model is called output oriented CCR model.
2. In this model, (φ=1, λ_j=0, λ_0=1) is a possible answer. As a result, Max$\varphi \geq 1$.
3. If we consider φ^* as the optimum solution of the above model, then there is (x_0, $\varphi^* y_0$) in T_C that generate ($\varphi y_0 > y_0$). This means that (x_0, φy_0) exceeds (x_0, y_0). Therefore, DMU_0 is not located on the boundary, and is inefficient.

3.5 Non-radial unoriented models

Models of this category deal with input and output variables at the same time. Slacks-based measure (SBM) and Super SBM models for the calculation between the time periods of $\delta^1(x_0,y_0)^t$ are expressed by the following fractional formula (Arabi 2015, Mirjalili *et al.* 2010)

$$\begin{aligned} & \delta^s((x_0,y_0)^t) = \min_{\lambda,\varphi,\phi}(1/1-\frac{1}{m}\sum_{i=1}^{m}\phi_i)/(1+\frac{1}{q}\sum_{r=1}^{q}\varphi_r) \\ & s.t: \sum_{j=1}^{n} \lambda_j x_{ij}^s = x_{i0}^t(1-\phi_i) \quad ,i=1,2,...,m \\ & \sum_{j=1}^{n} \lambda_j y_{ij}^s = y_{i0}^t(1+\varphi_i) \quad ,r=1,2,...,q \\ & L \le e\lambda \le U \\ & \lambda \ge 0, \varphi \ge 0, \phi \ge 0 \end{aligned} \tag{10}$$

This model can be converted to the linear mode. However, these models evaluate four states $[\delta^1(x_0,y_0)^1, \delta^2(x_0,y_0)^2]$ and $[\delta^1(x_0,y_0)^2, \delta^2(x_0,y_0)^1]$. We use SBM to solve this model, and if solving through this method proves to be impossible; then, we use Super SBM model (Arabi 2015, Charnes *et al.* 1984)

$$\begin{aligned} & \delta^s((x_0,y_0)^t) = \min_{\lambda,\varphi,\phi}(1/1+\frac{1}{m}\sum_{i=1}^{m}\phi_i)/(1-\frac{1}{q}\sum_{r=1}^{q}\varphi_r) \\ & s.t: \sum_{j=1}^{n} \lambda_j x_{ij}^s = x_{i0}^t(1+\phi_i) \quad ,i=1,2,...,m \\ & \sum_{j=1}^{n} \lambda_j y_{ij}^s = y_{i0}^t(1-\varphi_i) \quad ,r=1,2,...,q \\ & L \le e\lambda \le U \\ & \lambda \ge 0, \varphi \ge 0, \phi \ge 0 \end{aligned} \tag{11}$$

Unoriented model of (3-10) always has a possible answer and in any case with variable returns to scale, it has at least one efficient DMU. But, under unrestrictive conditions at least two units must have positive values for each output of (r=1, 2, ..., q) (Arabi 2015, Charnes *et al.* 1984).

3.6 The concept of returns to scale in DEA models

"Returns to scale" is a very important concept in the economy related studies. In the field of data envelopment analysis, when the inputs of a unit (DMU) change, it has an impact on the output of that unit, and this impact represents the type of returns to scale of the unit.

In a more simple and clear definition, "returns to scale" is the impact of all factors of production on output. In other words, "returns to scale" describes the response of output to a proportional increase in all inputs. For a particular change in combination of inputs, when the output increases with the same rate, the returns-to-scale is constant, when the output increases in lower rates than that proportion, the returns-to-scale is decreasing, and when the output increases in higher rates than that proportion, the returns-to-scale is increasing.

To clarify this concept, suppose that the production function is as follows (Arabi 2015)

$$y=f(x_1, x_2, \dots, x_n) \tag{12}$$

where y represents the output or the amount of production, and (x_1, x_2, …, x_n) represents the inputs or factors of production. Now, if we assume all inputs to change by λ, the changes in output or production value (y) may be in one of the three following forms (Ramazankhani *et al.* 2016, Rezaei-Shouroki *et al.* 2017, Mirjalili *et al.* 2010)

1. If the changes in the inputs (λ) cause the same amount of change in outputs (y), the production function has constant returns-to-scale (CRS). For example

$$f(\lambda x_1, \lambda x_2, ..., \lambda x_n) = \lambda y(x_1, x_2, ..., x_n) \tag{13}$$

2. If the changes in the inputs (λ) cause changes greater than λ in outputs (y), the production function has increasing returns-to-scale (IRS). For instance

$$f(\lambda x_1, \lambda x_2, ..., \lambda x_n) \succ \lambda y(x_1, x_2, ..., x_n) \tag{14}$$

3. If the changes in the inputs (λ) cause changes lower than λ in outputs (y), the production function has decreasing returns to scale (DRS), i.e.,

$$f(\lambda x_1, \lambda x_2, ..., \lambda x_n) \prec \lambda y(x_1, x_2, ..., x_n) \tag{15}$$

4. Analysis

In this study, the mentioned model is used to prioritize the location of installation of wind turbines in windy cities of Khorasan Razavi, Northern Khorasan and Southern Khorasan provinces.

In this regard, first, the criteria related to the construction of wind power plants should be determined. Inappropriate selection of criteria can significantly affect the final efficiency score and ranking of units. In this study, 9 factors of wind speed, topography of the area, the distance to the power distribution network, land price per square meter, the rate of natural disasters, air temperature, air pollution, the distance to the main roads, and favorable wind direction are used as decision making criteria, and are considered in DEA model. These criteria are selected with the help and guidance and opinions of experts in Iran Renewable Energy Organization, Applied Meteorology Department, Natural Resources department in the provinces of Khorasan Razavi, Northern Khorasan and Southern Khorasan, Tehran Electrical Distribution Co., and also by considering the opinions of turbine experts and University professors. Each of these criteria will be described and determined in the following.

First, values of DEA model variables for each unit will be mentioned, and then the results of DEA model and eventually the final rankings of units will be presented. In this paper, dual DEA model, the model of Anderson-Patterson and the softwares of Excel 2010 and DEA Solver are used.

4.1 Decision making units and variables

10 cities of Esfaraen, Bojnoord, Davarzan, Sarakhs, Ghadamgah, khaf, Rudab, Afriz, Fadashk,and Nehbandan in the provinces of Khorasan Razavi, Northern Khorasan, and Southern Khorasan are studied. In each city, one location was determined as a suitable position for the plant, and each of these locations was considered as one decision making unit (DMU). As a result, 10 DMUs will be ranked in this DEA model. These DMUs are represented with the symbols shown in Table 2. Latitude and longitude of each DMU indicate its exact position on the map. In this table, based on the initial assumption that was mentioned in the first chapter, the values of meteorological parameters at different locations around each particular city were considered identical. So, it can be seen that difference of values in different locations around each city are just related to their distance from main road and power network.

As mentioned in the previous chapter, factors of wind speed, topography of the area, the distance to the power distribution network, land price per square meter, the rate of natural disasters, air temperature, air pollution, the distance to the roads, and favorable wind direction are considered as input variables for DEA model. These variables are entered into DEA model as presented in Table 3.

Table 2 Characteristics of DMUs

Name	DMU Symbol
Esfaraen	DMU_{01}
Bojnoord	DMU_{02}
Davarzan	DMU_{03}
Sarakhs	DMU_{04}
Ghadamgah	DMU_{05}
Khaf	DMU_{06}
Rudab	DMU_{07}
Afriz	DMU_{08}
Fadashk	DMU_{09}
Nehbandan	DMU_{10}

Table 3 Variables of the problem

Variable name	Variable symbol	Variable type
Air temperature	I1	Input
Land price	I2	Input
Distance to power grid	I3	Input
Distance to main road	I4	Input
Pollution	I5	Input
Rate of natural disasters	I6	Input
Wind speed	O1	Output
Favorable wind direction	O2	Output
Topographical condition	O3	Output

Table 4 The temperature of cities (Arabi 2015)

City	Air temperature (℃)
Esfaraen	17.26
Bojnoord	13.30
Davarzan	18.68
Sarakhs	18.75
Ghadamgah	15.56
Khaf	18.59
Rudab	18.33
Afriz	17.69
Fadashk	18.87
Nehbandan	20.35

4.2 The values of different variables for each DMU

In this section, the values of different variables of DEA model were compared for each DMU (different cities).

4.2.1 Air temperature

Studies show that wind speed decreases with the increase of air temperature, which leads to the reduction of electricity generated by the turbine (Ghasemi-Far 2013). In this study, the average temperature of the city is used as a criterion for prioritization. Therefore, this variable is considered as an input for DEA model, because an increase in this variable reduces the efficiency of related DMU.

Average daily air temperatures for different cities are presented in Table 4. These values are expressed in degrees Celsius. As can be seen in this Table, Nehbandan with an average temperature of 20.35 ℃ is the warmest city, and Bojnoord with the average temperature 13.30℃, is the coldest city.

4.2.2 Distance to electric grid

The distance between the wind farm and power distribution network is another important criterion in the construction of wind power plant. It is obvious that lower distance between wind farm and power distribution network means lower costs of connecting it to the grid. Wind farms must usually be connected to 20 kV substations of the city. These substations are always located within the city and each city has a large number of these substations. Thus, in this study, the distance of location of wind farm from the center of the city (km) is considered as the parameter of distance to power grid. The increased value of this criterion decreases the chance of location to be selected as the site of wind farm; therefore, this criterion acts as a denominator in objective function and is considered as an input for the DEA model. Values of distance to power grid for different DMUs are shown in Table 5. As can be seen from Table 5, Afriz site has the highest distance to power grid (2,524 meters) and Esfaraen has the lowest distance to power grid (1,423 meters).

Table 5 The distance of each DMU to power grid (Arabi 2015)

DMU	Distance to power grid (m)
Esfaraen	1,423
Bojnoord	1,720
Davarzan	2,340
Sarakhs	2,300
Ghadamgah	1,930
Khaf	1,430
Rudab	2,440
Afriz	2,524
Fadashk	2,500
Nehbandan	1,587

Table 6 The distance of each DMU to main road (Arabi 2015)

DMU	Distance to main road (m)
Esfaraen	324
Bojnoord	251
Davarzan	306
Sarakhs	185
Ghadamgah	132
Khaf	125
Rudab	652
Afriz	722
Fadashk	526
Nehbandan	225

Table 7 The amount of air pollution in cities (Arabi 2015)

City	The amount of air pollution (tons)
Esfaraen	17,258.42

Table 7 Continued

City	The amount of air pollution (tons)
Bojnoord	198,452.50
Davarzan	752.43
Sarakhs	9,632.25
Ghadamgah	2,479.83
Khaf	345.43
Rudab	321.01
Afriz	214.52
Fadashk	313.02
Nehbandan	28,532.93

4.2.3 Distance to main road

Constructing wind turbines requires all equipment and devices related to turbines and other materials and tools needed for their installation to be transferred to the site of wind farm. In case of lack of access to the desired location via the existing road network, new roads should be built which will impose a tremendous amount of additional costs. Therefore, the locations closer to the road networks are more favorable. Here, the closest possible route to the main roads is used as a criterion for prioritizing options. Therefore, this variable is considered as an input for DEA model. The values of distance of each DMU to main road are shown in Table 6. As can be seen from Table 6, Rudab site has the highest distance to main road (652 meters) and Khaf has the lowest distance to main road (125 meters).

4.2.4 The amount of air pollution

Pollution and dust in the air reduce the wind speed; thus, they lead to reduced energy received by wind turbines. Therefore, the plant should be built in a place that has the least amount of pollution and dust.

Detailed information about the amount of air pollution in cities across the studied provinces is not available; thus, population and per capita carbon dioxide emissions of each city were used as a criterion to estimate the amount of pollution and to perform an approximate comparison between cities in this regard. Results of population and housing census were used to obtain the required data about the population of cities. Additionally, the report of European commission's joint research center regarding global CO_2 pollution (2012) was used to obtain information about the amount of per capita production of pollution (Sadeghi 2012, Irimo 2016).

This variable is considered as an input for DEA model, because an increase in this variable will decrease the efficiency of the DMU. The values related to the amount of (CO_2) pollution in each city are shown in Table 7. It is evident from Table 7 that Bojnoord has the highest emission of (CO_2) pollution (198,452.50 tons) and Afriz has the lowest emission of (CO_2) pollution (214.52 tons).

4.2.5 Wind speed

Wind potential at the candidate sites is one the important criteria by which the locations can be assessed in terms of potential wind power. Wind speed is one of the most important data that can represent the wind potential of a region. According to experts, installing turbines in areas with mean wind speeds less than a certain value (cut-in speed which is usually between 3 to 5 m/s for most commercial wind turbines) is not viable, because in wind speeds less than this value, turbine blades do not even start moving. Of course, these wind speeds can also produce electricity if the blades are made by lighter nanomaterial. The maximum wind speed (cut-out speed) should also be considered. Turbines are generally conFig.d in a way that they will shut down at wind speeds higher than this value to avoid any possible damage. Another important issue is the statistical distribution of wind speed. Favorable wind speed alone is not enough to produce wind energy, and its frequency and duration are also important. The amount of producible wind energy depends on the elements of wind speed, but also on-air pressure and temperature in the region (Rezaei-Shouroki *et al.* 2017, Mostafaeipour 2011, Mohammadi *et al.* 2014, Movahedi and Hosseini 2010).

In this study, the mean wind speed is used as a criterion for the prioritization. This factor is considered as an output variable for DEA model, because increasing this variable will increase the efficiency of DMU.

Wind speed data related to winds at up to 40 meters above the ground are valid within a 7.5 km radius of the location of measurement (weather station); thus, all related criteria should be examined in this range, and wind speeds (and also wind powers) obtained outside this range are not valid. Other criteria cannot also be used outside this range. Wind speed is a random variable, and probability density functions can be used to calculate the wind power of an area. Wind speed can be evaluated through different types of frequency distribution, such as Weibull-Rayleigh distribution, 3-parameter Beta distribution, Log-normal distribution, and gamma distribution. The use of Weibull distribution is very common and provides a high accuracy (Arabi 2015, Movahedi and Hosseini 2010). Weibull probability distribution function is defined as (Movahedi and Hosseini 2010)

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{V}{c}\right)^{k-1} e^{-\left(\frac{V}{c}\right)^{k}} \tag{16}$$

where *f*(*v*) is the probability density function, and *V* is the wind speed. In this equation, there are two fixed parameters *c* and *k*, i.e., scale parameter and shape parameter, which must be determined at first. *k* and *c* can be easily calculated from the following equations (Mirjalili *et al.* 2010, Farrell 1957)

$$k = \left(\frac{\sigma}{v}\right)^{-1.086} \tag{17}$$

$$c = \frac{v}{\Gamma(1+\frac{1}{k})} \tag{18}$$

In Eq. (17), σ is the standard deviation of wind speed, and in equation (18), Γ is the gamma function which is in the form of following equation (Mirjalili *et al.* 2010, Farrell 1957)

$$\Gamma_{(x)} = \int_0^{\infty} e^{-u} u^{x-1} du) \tag{19}$$

In order to calculate *k* and *c*, annual mean wind speed for the available data should first be acquired (because we need wind power based on an annual basis), and then, should be inserted in Eqs. (17) and (18) for each year. We use the following equations to convert wind speed at 40 meters height to wind speed at 70 meters height (Arabi 2015)

$$k_h = k_o\left[1-0.088\ln\left(\frac{h_o}{10}\right)\right]\Big/\left[1-0.088\ln\left(\frac{h}{10}\right)\right] \quad (20)$$

$$c_h = c_o\left(\frac{h}{h_o}\right)^n \quad (21)$$

In Eqs. (20) and (21), k_h and c_h are the shape parameter and scale parameter at the desired height (70 meters) respectively, and k_o and c_o are the shape parameter and scale parameter for the height at which data is measured.

In Eq. (21), n is the power law index which can be obtained by the following equation (Arabi 2015)

$$n = \left[0.37-0.088\ln\left(c_o\right)\right]\Big/\left[1-0.088\ln\left(\frac{h}{10}\right)\right] \quad (22)$$

To use wind potential as a criterion for the prioritization, we must determine a value that can represent this criterion for a particular zone. For this purpose, the mean wind power obtained for all years is applied in DEA model. We know that higher wind potential of a site means that it is more suitable for the construction of wind farm. Therefore, the type of this criterion (in terms of being input or output) should be in a way that increasing, it leads to the increase of objective function. As a result, this criterion should be considered as an output, and it will be inserted in the objective function as a denominator.

Table 8 shows the values of the mean wind speed per day at the height of 40 meters for different DMUs. According to the comparison of wind speeds, at this height, Khaf has the highest wind speed (10.82 meters per second) and Davarzan has the lowest wind speed (4.19 meters per second) among the studied cities.

Table 9 lists the values of the mean wind speed per day at the height of 70 meters for different DMUs. According to the comparison of wind speeds, at this height, Khaf has the highest wind speed (12.29 meters per second) and Davarzan has the lowest wind speed (4.66 meters per second) among the studied cities (Arabi 2015).

Table 8 Wind speed at the height of 40 meters in different cities (Arabi 2015)

City	Wind speed (m/s)
Esfaraen	4.37
Bojnoord	5.56
Davarzan	4.19
Sarakhs	4.80
Ghadamgah	5.25
Khaf	10.82
Rudab	6.20
Afriz	5.42

Table 8 Continued

City	Wind speed (m/s)
Fadashk	6.33
Nehbandan	5.86

Table 9 Wind speed at the height of 70 meters in different cities (Arabi 2015)

City	Wind speed (m/s)
Esfaraen	5.13
Bojnoord	6.67
Davarzan	4.66
Sarakhs	5.41
Ghadamgah	5.67
Khaf	12.29
Rudab	4.44
Afriz	6.40
Fadashk	7.23
Nehbandan	6.6

Table 10 Dominant wind direction at the height of 37.5 meters in different cities

City	Wind direction (°)
Esfaraen	137.13
Bojnoord	162.88
Davarzan	185.50
Sarakhs	216.57
Ghadamgah	221.25
Khaf	90.03
Rudab	129.68
Afriz	140.83
Fadashk	276.01
Nehbandan	166.28

4.2.6 Wind direction

Wind direction is another important criterion for the installation of wind turbines. The position in which turbines are going to be installed should have favorable wind direction. This factor leads to higher efficiency and it must be considered as an output.

Average values related to wind direction for different DMUs are shown in Table 10. Dominant wind direction in each city is obtained according to the meteorological data gathered from the height of 37.5 meters. In this category, Fadashk has the highest value (276.1 degrees) and Khaf has the lowest value (90.03 degrees).

4.2.7 Rate of natural disasters

Rate of natural disasters affects the priorities for the construction of wind power plant. Lower

Table 11 The rate of natural disasters in different cities

City	Rate of natural disasters
Esfaraen	6.1
Bojnoord	8.2
Davarzan	7.2
Sarakhs	6.28
Ghadamgah	6.3
Khaf	4.6
Rudab	7.4
Afriz	5.1
Fadashk	6.45
Nehbandan	5.2

Table 12 The topography criterion for different cities

City	Topography criterion
Esfaraen	166.38
Bojnoord	121.77
Davarzan	170.16
Sarakhs	165
Ghadamgah	167.44
Khaf	171.16
Rudab	135.14
Afriz	156.15
Fadashk	160
Nehbandan	164.35

rates of natural disasters such as floods and earthquakes in a region lead to higher priority of that region for the installation of wind turbines. It is obvious that constructing wind farms in areas that have a high probability of natural disasters increases the likelihood of damage, failure and loss. According to experts and published researches, floods and earthquakes are two of the most important natural disasters in this regard. Thus, the cities that don't have a good condition in this respect have a lower chance of being selected as the location of wind farm. Higher likelihood of natural disasters in a city means that it should have a lower priority; therefore, this factor is a decreasing criterion and should be considered as an input for DEA model.

Values related to the rate of natural disasters for different cities are shown in Table 11. According to Table 11, Bojnoord has the highest average rate of natural disasters (8.2), and Khaf has the lowest average rate of natural disasters (4.6).

4.2.8 The topography of the region

The topography of the region is another important criterion in the construction of wind power plants. A good location for the construction of wind turbines must have many qualification and favorable conditions; some of these conditions can be artificially improved by spending extra funds, time, and effort, but for others, this is not possible, which means that turbines cannot be built there. According to turbine experts of wind power management office, turbines should be built in areas that are desirable in terms of soil type and degree of compactness. But the absence of these requirements can be compensated by building adequate foundation. The ground at which structure is going to be built must be completely horizontal (slope of zero).

This requirement should be especially observed for turbines which have a significant height. But, since we can rarely find an absolutely horizontal piece of land in an area (especially in a small area of about 2,000 square meters), this slope of zero should be created with appropriate construction operations. The cost of creating proper conditions for soil and slope are very small compared with the total costs; thus, we cannot rule out a site just, because it lacks the proper topographical conditions in its natural form.

According to the related findings and studies, a wind plant should not be built in areas with little or no tree cover, because collision of broken parts of the trees to the turbine can damage it. Urban and residential areas are also not suitable for the construction of wind power plants and are excluded from the list of candidate sites.

In this study, the mentioned issues are taken into account and the area of regions which don't have the right conditions are calculated and considered as a criterion for the evaluation of topography. Evaluation of criteria for each city should be carried out within a circular area with a radius of 7.5 km centered at the meteorological station of that city. Furthermore, the criterion of the topography for each city is represented by the area of suitable regions in the area around that city (in square kilometers). Any city which has a more suitable condition in this respect will be a more appropriate place to build wind farm. With these explanations, it is clear that this is criterion must be considered as an output for DEA model, because its rising will increase the probability of selecting that city as the location of wind farm.

Values related to the topography of each region are presented in Table 12. These data are also depicted as a graph.

4.2.9 Land price

Constructing a wind farm requires a large piece of land; therefore, the price of land is another criterion of this study. Thus, selecting a location with a lower land price is a priority. Decreasing this criterion increases the objective function of DEA model, and it is considered as an input and will be inserted in the objective function as a denominator. In this research, the price of one square meter of land in the area (in each DMU) is considered as a criterion for the prioritization.

Values related to the land price in different cities are shown in Table 13. As shown in Table 13, Ghadamgah has the highest average land price (300 $ per square meter), and Afriz has the lowest average land price (67$ per square meter).

Table 13 Land prices in different cities

City	Land price ($)
Esfaraen	234
Bojnoord	267
Davarzan	134
Sarakhs	200
Ghadamgah	300

Table 13 Continued

City	Land price ($)
Khaf	167
Rudab	100
Afriz	67
Fadashk	100
Nehbandan	267

5. Discussion

DEA Solver software is used for all calculations regarding data envelopment analysis. Data envelopment analysis softwares are divided into two categories: (1) Operations research software – such as GAMS and LINGO. In this category, DEA models need to be coded and run within the environment of the software and then, optimal values of parameters and efficiency values can be calculated. (2) Softwares such as DEA Frontier, DEA Max, DEA P and DEA Solver. These softwares don't need any coding, and specifying the input and output variables for each DMU and target model is enough for the automatic analysis of data based on specified model and presenting various outputs including the calculation of efficiency of each DMU, ranking of DMUs, identification of reference DMUs and inefficient DMUs, the calculation of model parameters and the optimum values of input and output variables, and presenting recommendations to improve the inefficient DMUs. Here, DEA Solver software is used in order to ensure the accurate calculation of model and also to take advantage of various outputs that this software provides. This software also allows us to avoid extensive coding, because this process is done automatically by software and software outputs will only be interpreted in regard with research questions and objectives. In the DEA Solver software, solving process is performed in two modes of primary (multiplicative) and secondary (dual). In secondary mode, values of λ will be used to obtain the inefficient units reference set, and the input slacks (S^-) and output slacks (S^+) will be used to calculate the optimal amounts of inputs and outputs of inefficient units.

Dual mode method has the following benefits (Charnes *et al.* 1978):

1. In linear programming (LP) method, the number of needed calculations increases with the number of constraints. In DEA method, the number of DMUs (n) is usually considerably larger than the number of inputs and outputs ($m+s$). In addition, the size of the memory required to store the base (or reverse) is equal to the square of the number of constraints. Therefore, using dual (DLP) method is also more appropriate in terms of required memory.

2. The LP method cannot provide the answer with the highest value of slack.

3. The DLP method is more straightforward, because its answer is expressed in the form of inputs and outputs corresponding to preliminary data, while the answer of LP method shows the evaluation of the data. Although these values are also important, but they are usually used for the analyses performed after DLP process.

5.1 BCC method

First, the cities of Khorasan province will be analyzed and ranked by BCC model through both primary and secondary modes (dual or envelopment). Primary and secondary modes of BCC model by which calculations are performed in DEA Solver software.

Table 14 Efficiency of different cities (BCC Model)

City	Efficiency	Rank
Khaf	1	1
Afriz	1	1
Ghadamgah	1	1
Fadashk	1	1
Sarakhs	1	1
Bojnoord	1	1
Nehbandan	1	1
Esfaraen	1	1
Davarzan	1	1
Rudab	0.875	2

Efficiency levels of each of the cities for the construction and installation of wind turbines are presented in Table 14.

As shown in Table 14, the efficiency of 9 cities is equal to 1, and Rudab is the only city that its efficiency is less than 1 and is inefficient. In BCC model, the number of DMUs should be three times the total number of inputs and outputs, for the efficient units to be properly selected as efficient frontier. However, given that the number of selected cities is less than three times the total number of inputs and outputs, some inefficient cities have been placed on efficient frontier due to the lack of sufficient DMUs. Thus, the efficiency level of most of the cities is obtained as 1. We use super-efficiency (Anderson-Peterson) method to rank the cities that had the efficiency of 1.

5.2 A-P (Anderson-Peterson) method

In this method, the limits of efficiency inside the model are removed, and the efficiency can be calculated to be more than 1. The results of Anderson-Peterson method calculated through both primary and secondary (dual) modes are shown in Table 15. It is obvious from Table 15 that Khaf has the highest efficiency among these cities (2.214), which is almost two times the efficiency of cities of Afriz (1.21), Ghadamgah (1.17), Fadashk (1.14), Sarakhs (1.049), Bojnoord (1.04), Nehbandan (1.026), Esfaraen (1.021), and Davarzan (1.019) and three times the efficiency of city of Rudab (0.72). The city of Rudab has the lowest efficiency (0.72) and is at the bottom of ranking. This city is at the bottom of ranking in both BCC method and Anderson-Peterson method.

In the DEA, and in the process of calculating the efficiency of units, some efficient units will be considered as a reference for inefficient units, and an index will be defined to represent the effectiveness of each of them. Therefore, the references of inefficient units will be selected from the same set of efficient units. In dual method, values of λ will be calculated for all units. Units that have a non-zero λ will be selected as the reference for inefficient units. The higher value of λ will result in increased effect of reference on that inefficient unit.

Reference units of inefficient cities are shown in Table 16. This means that these reference units act as a model for cities that are inefficient. For example, reference units for the city of Davarzan are the cities of Khaf, Fadashk and Sarakhs with the index of 0.47, 0.48 and 0.05, respectively. The higher value of this index for a city, results in an increased effect of inputs and outputs of that city as a reference.

Based on the value of λ, reference units for the city of Esfaraen are Khaf (0.61), Ghadamgah (0.32), Bojnoord (0.07) and Nehbandan (0.01). Thus, the city of Khaf – which has a higher λ – has a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Bojnoord are Ghadamgah (0.58), Esfaraen (0.17) and Khaf (0.17) which show that Ghadamgah with a higher λ, has a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Davarzan are Fadashk (0.48), Khaf (0.47) and Sarakhs (0.05) showing that Fadashk and Khaf have a higher λ, and also have a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Sarakhs are Ghadamgah (0.76), khaf (0.06), Fadashk (0.01) and Davarzan (0.07) showing that Ghadamgah with a higher λ, has a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Ghadamgah are Khaf (0.77), Sarakhs (0.23) showing that Khaf, which has a higher λ, has a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Rudab are Afriz (0.41), Khaf (0.02), Fadashk (0.39) and which show that Afriz and Fadashk , which have a higher λ, have a greater influence as a reference on improving the inputs and outputs.

Fadashk is determined as the reference unit for the city of Afriz which can influence it as a reference, and changes and improves its inputs and outputs. Based on the value of λ, reference units for the city of Fadashk are Khaf (0.24), Davarzan (0.12), Afriz (0.63) and which show that Afriz, which has a higher λ, has a greater influence as a reference on improving the inputs and outputs. Based on the value of λ, reference units for the city of Nehbandan are Khaf (0.42), Ghadamgah (0.52) which show that Ghadamgah, which has a higher λ, has a greater influence as a reference on improving the inputs and outputs.

Table 15 Efficiency of different cities (Super efficiency model)

City	Efficiency	Rank
Khaf	2.21481	1
Afriz	1.21499	2
Ghadamgah	1.17729	3
Fadashk	1.14749	4
Sarakhs	1.04944	5
Bojnoord	1.04004	6
Nehbandan	1.02645	7
Esfaraen	1.02186	7
Davarzan	1.01903	9
Rudab	0.72332	10

Table 16 Reference units for inefficient cities

City	Efficiency	Reference units for inefficient cities
Esfaraen	1.0219	Khaf (0.61), Ghadamgah (0.32), Bojnoord (0.07) Nehbandan (0.01)
Bojnoord	1.04	Ghadamgah (0.58), Khaf (0.17), Esfaraen (0.25)

Table 16 Continued

City	Efficiency	Reference units for inefficient cities
Davarzan	1. 019	Khaf (0.47), Fadashk (0.48), Sarakhs (0.05)
Sarakhs	1.0494	Ghadamgah (0.76), Khaf (0.06), Fadashk (0.1), Davarzan (0.07)
Ghadamgah	1.1773	Khaf (0.77), Sarakhs (0.23)
Khaf	2.2148	–
Rudab	0.7233	Afriz (0.41), Fadashk (0.39), khaf (0.2)
Afriz	1. 215	Fadashk (1)
Fhadashk	1.1475	Khaf (0.24), Afriz (0.63), Davarzan (0.12)
Nehbandan	1.0265	Khaf (0.42), Ghadamgah (0.58)

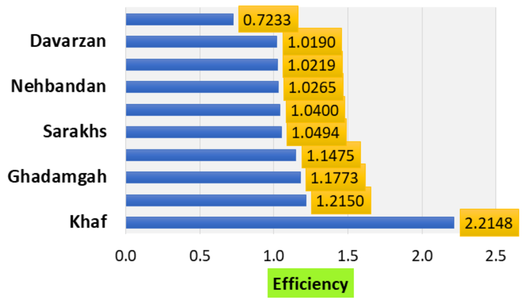

Fig. 2 Ranking of cities based on efficiency

Fig. 2 shows the prioritization of installation of wind turbines in the cities of Khorasan province based on efficiency obtained through Anderson-Peterson method. The city of Khaf with an efficiency of 2.21 is in the first place, and the city of Afriz with an efficiency of 0.72 is in the last place of this ranking, and the cities of Ghadamgah, Fadashk, Sarakhs, Bojnoord, Nehbandan, Esfaraen and Davarzan with the efficiencies of 1.21, 1.17, 1.14, 1.049, 1.026, 1.02, and 1.01, are in the second to ninth place in the ranking of suitable location for the installation of wind turbines, respectively.

5.3 Optimum values of inputs

Table 17 shows the optimum values of inputs for inefficient cities. If the inputs of inefficient cities change in an optimal way, their efficiency will increase. “Change%” column shows the amount of changes in the input in terms of percent. The optimum amount of inputs and outputs of inefficient units is obtained through eliminating scale inefficiency by multiplying efficiency value by input and output, and then obtaining optimal inputs and outputs by reducing the input slacks (S^-) and adding the output slacks (S^+) which actually also leads to elimination of combination inefficiency. Optimal values for inefficient units reported by DEA Solver software are shown in Tables 17. “Change%” columns present the amount of required changes on any input and output in order to achieve the optimum level.

According to Table 17, the greatest changes in each variable are as follows:

1. In the variable of air temperature, the city of Bojnoord has the greatest change (24%).

2. In the variable of land price, the city of Ghadamgah has the greatest change (41%).
3. In the variable of distance to electrical grid, the city of Ghadamgah has the greatest change (15%).
4. In the variable of distance to main road, the city of Esfaraen has the greatest change (57%).
5. In the variable of air pollution, the city of Bojnoord has the greatest change (97%).
6. In the variable of rate of natural disasters, the city of Bojnoord has the greatest change (27%).

Table 17 Optimum values of inputs

	Distance to power grid			Land price			Temperature		
City	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value
Esfaraen	13.12%	1609.6	1423	-7.21%	649,556.47	700000	0.00%	17.26	17.26
Bojnoord	0.00%	1720	1720	2.19%	782,468.62	800000	24.03%	16.50	13.3
Davarzan	15.14%	1985.7	2340	2.02%	408,070.89	400000	0.25%	18.73	18.68
Sarakhs	13.52%	1989.1	2300	29.66%	777,971.21	600000	13.03%	16.31	18.75
Ghadamgah	15.55%	1629.9	1930	41.89%	522,978.15	900000	19.71%	18.63	15.56
Khaf	0.00%	1430	1430	0.00%	500000	500000	0.00%	18.59	18.59
Rudab	6.05%	2292.5	2440	0.00%	300000	300000	0.00%	18.33	18.33
Afriz	0.95%	2499.9	2524	50.00%	299997	200000	6.61%	18.86	17.69
Fadashk	10.53%	2236.7	2500	0.88%	297,368.19	300000	4.40%	18.03	18.86
Nehbandan	8.41%	1720.5	1587	8.45%	732,431.82	800000	17.30%	16.83	20.35
	The rate of natural disasters			air pollution			Distance to main road		
City	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value
Esfaraen	11.48%	5.40	6.1	10.32%	15478.0	17258.42	57.77%	136.8	324
Bojnoord	27.32%	5.96	8.2	97.11%	5741.9	198452.5	29.11%	177.9	251
Davarzan	22.66%	5.57	7.2	0.00%	752.49	752.43	4.95%	321.2	306
Sarakhs	0.00%	6.28	6.28	79.20%	2004.0	9632.25	0.00%	185.0	185
Ghadamgah	20.86%	4.987	6.3	0.00%	2479.8	2479.83	5.14%	138.8	132
Khaf	0.00%	4.60	4.6	0.00%	345.4	345.43	0.00%	125.0	125
Rudab	25.32%	5.53	7.4	12.90%	279.6	321.01	19.61%	524.1	652
Afriz	26.47%	6.45	5.1	45.92%	313.0	214.52	27.15%	526.0	722
Fadashk	18.76%	5.24	6.45	0.00%	313.0	313.02	0.00%	526	526
Nehbandan	7.46%	5.59	5.2	94.44%	1585.7	28532.93	42.64%	129.1	225

Table 18 Optimum values of outputs

	Wind speed			Wind direction			Topography		
City	Change (%)	Change (%)	Change (%)	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value
Esfaraen	0.00%	0.00%	0.00%	90.32%	9.7635255	5.13	98.05%	8.6549561	4.37

Table 18 Continued

City	Wind speed			Wind direction			Topography		
	Change (%)	Change (%)	Change (%)	Change (%)	Optimal value	Initial value	Change (%)	Optimal value	Initial value
Bojnoord	37.81%	37.81%	37.81%	0.00%	6.67	6.67	7.68%	5.9869141	5.56
Davarzan	2.74%	2.74%	2.74%	104.63%	9.535954	4.66	100.00%	8.3800607	4.19
Sarakhs	1.26%	1.26%	1.26%	13.68%	6.1502577	5.41	16.97%	5.6147718	4.8
Ghadamgah	1.38%	1.38%	1.38%	88.86%	10.708637	5.67	79.74%	9.4363064	5.25
khaf	6.46%	6.46%	6.46%	41.36%	7.2065918	12.29	41.65%	6.3137811	10.82
Rudab	18.91%	18.91%	18.91%	22.98%	7.9201741	6.44	10.84%	6.8719909	6.2
Afriz	2.46%	2.46%	2.46%	12.97%	7.2299277	6.4	16.79%	6.3299367	5.42
Fadashk	0.95%	0.95%	0.95%	5.22%	7.6073252	7.23	3.83%	6.5722838	6.33
Nehbandan	2.83%	2.83%	2.83%	27.92%	8.4430477	6.6	29.41%	7.583209	5.86

Table 19 Descriptive parameters of input and output variables

Criterion	Standard deviation	Mean	Minimum	Maximum
Temperature	1.89	17.737	13.3	20.35
Land price	233452.35	550000	200000	900000
Distance to grid	427.98	2019.4	1423	2524
Distance to main road	203.39	344.8	125	722
Air pollution	58243.65	25830.23	214.52	198452.5
Rate of natural disasters	1.06	6.283	4.6	8.2
Wind speed at the height of 40 meters	1.78	5.88	4.19	10.82
Wind speed at the height of 70 meters	2.03	6.65	4.66	12.29
Wind direction	51.21	172.62	90.03	276.01
Topography	15.53	157.76	121.77	171.16

5.4 Optimum values of outputs

Optimal values of outputs calculated for inefficient units are shown in Tables 18. If the outputs of inefficient cities change in an optimal way, their efficiency will increase. Changes in % for columns show the amount of changes in the outputs in terms of percent.

According Table 18, the greatest changes in each variable are as follows:

1. In the variable of Wind speed at the height of 40 meters, the city of Davarzan has the greatest change (100%).
2. In the variable of Wind speed at the height of 70 meters, the city of Esfaraen has the greatest change (90%).
3. In the variable of Wind direction, the city of Afriz has the greatest change (95%).
4. In the variable of topography, the city of Bojnoord has the greatest change (37%).

5.5 Descriptive statistics of input and output variables

Table 19 lists the descriptive parameters (mean, standard deviation, maximum and minimum) for the input and output variables.

5.6 Correlation between inputs and outputs

Pearson's correlation coefficient was used to assess the correlation between input variables and output variables. Assessing the correlation between input and output variables is a necessary procedure in the process of improving these variables. There is a significant negative relationship between the variables of land price and distance to grid, and also between the variables of land price and distance to main road; there is also a significant negative relationship between the variables of temperature and air pollution. Therefore, decreasing one of them will increase the other and this issue should be considered in the process of changing inputs. Table 20 provides the degree of correlation between input variables and output variables.

In Table 20, significant correlations are marked with asterisk. Other correlation coefficients between variables are not significant (Correlation coefficient is a value between 1 and -1). If its sign is positive, the relationship between the two variables is positive, and if the sign is negative, the relationship between the two variables is invers. Significant relationships are as follows:

1. There is a significant negative correlation between the variables of “land price” and “distance to grid” with a correlation coefficient of -0.711 and significance level of 95%.
2. There is a significant negative correlation between the variables of “temperature” and “air pollution” with a correlation coefficient of -0.734 and significance level of 95%.
3. There is a significant negative correlation between the variables of “land price” and “distance to main road” with a correlation coefficient of -0.792 and significance level of 99%.
4. There is a significant negative correlation between the variables of “distance to grid” and “distance to main road” with a correlation coefficient of -0.678 and significance level of 95%.
5. There is a significant negative correlation between the variables of “air pollution” and “topographical conditions” with a correlation coefficient of -0.741 and significance level of 95%.
6. There is a significant negative correlation between the variables of “rate of natural disasters” and “topographical conditions” with a correlation coefficient of -0.679 and significance level of 95%.
7. There is a significant positive correlation between the variables of “wind speed at the height of 40 meters” and “wind speed at the height of 70 meters” with a correlation coefficient of 0.992 and significance level of 95%.

Table 21 shows the final results of prioritization for installing wind turbine; as can be seen in this table, the city of Khaf has the highest ranking in this regard.

Table 20 The correlation between input variables and output variables

Criterion	Topography	Wind speed at the height of 70 meters	Wind speed at the height of 40 meters	Rate of natural disasters	Air pollution	Distance to main road	Distance to grid	Land price	Temp
Temperature	0.584	0.127	0.167	-0.547	*-0.734	0.145	0.189	-0.416	1
Land price	0.023	-0.133	-0.147	0.092	0.444	**-0.792	*-0.711	1	
Distance to grid	-0.139	-0.373	-0.338	0.273	-0.317	*0.678	1		

Table 20 Continued

Criterion	Topography	Wind speed at the height of 70 meters	Wind speed at the height of 40 meters	Rate of natural disasters	Air pollution	Distance to main road	Distance to grid	Land price	Temp
Distance to main road	-0.36	-0.188	-0.178	0.098	-0.205	1			
Air pollution	-0.741	-0.032	-0.098	0.562	1				
Rate of natural disasters	-0.679	-0.503	-0.488	1					
Wind speed at the height of 40 meters	0.87	*0.992	1						
Wind speed at the height of 70 meters	0.079	1							
Topography	1								

*: Significant at the 95 percent confidence level

**: Significant at the 99 percent confidence level

Table 21 Results of DEA method

Unit	City	Rank in DEA
DMU_1	Esfaraen	8
DMU_2	Bojnoord	6
DMU_3	Davarzan	9
DMU_4	Sarakhs	5
DMU_5	Ghadamgah	3
DMU_6	Khaf	1
DMU_7	Rudab	10
DMU_8	Afriz	2
DMU_9	Fadashk	4
DMU_{10}	Nehbandan	7

5.7 Hydrogen production for the city of Khaf

Due to the stochastic behavior of wind, storing wind power generated by wind turbines in an energy carrier can enhance the amount of energy output. Hydrogen is actually an energy carrier that can be used to store and provide energy. The ability of extrication of hydrogen from a variety of renewable energies, fossil fuel and nuclear power highlights its obvious advantages. Nevertheless, hydrogen will play an important role in progress towards sustainable energy developments. Electrolyzers are responsible to produce hydrogen from renewable forms of energy using the electrolysis process. By utilizing this process, water in the presence of an anode and a

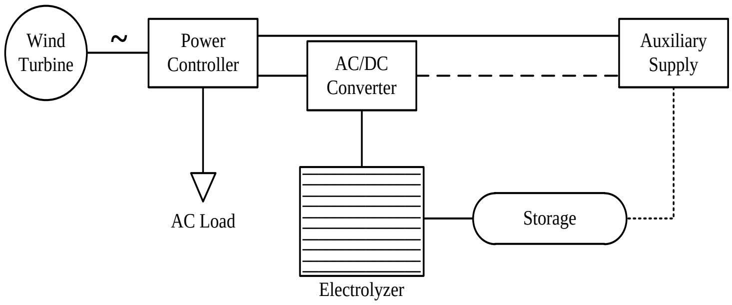

Fig. 3 The proposed wind-to-hydrogen system

cathode will split into hydrogen and oxygen, which this method performs effectively for large scales (Yang *et al.* 2015).

In this paper, a stand-alone wind-to-hydrogen system is examined to assess the performance of different wind turbines so as to hydrogen production (Alavi *et al.* 2016a). Fig. 3 shows the proposed energy conversion system. As seen, this system is comprised of four major components: a wind turbine, a power electronic converter, control system, and a water electrolyzer. The converter's major task is to reduce the output voltage of the wind turbine to a lower level, which provides the required current level for the electrolyzer. Although the hydrogen production rate will be higher with the greater amount of the electrolyte voltage, it will decrease the electrolyzer efficiency (Barbir 2005).

The utilizing this energy system will give a linear relationship between the wind power output and the amount of hydrogen production as follows (Gupta-Ram 2009)

$$H_2 = E_{WT} \times \frac{\eta_{Conv}}{ec_{el}} \tag{26}$$

where H_2 is the amount of hydrogen production (Nm^3), E_{WT} is the wind turbine annual energy (kWh), η_{Conv} is the rectifier efficiency, and ec_{el} is the energy consumed by the electrolyzer. A rectifier with the efficiency of 95% and an electrolyzer with 5 kWh/Nm^3 energy consumption are the assumption of the analysis.

In order to estimate the wind turbine annual energy, first, the average wind power output should be calculated; then, the annual energy will be determined by multiplying the average power by the hours (Burton *et al.* 2011). Additionally, downtime losses (6%), array losses (5%), icing/soiling losses (4%), and other probable losses (4%) are assumed in the analysis. The average wind power output can be predicted by (Burton *et al.* 2011)

$$P_{WT} = \int_0^{\infty} f(v)\, P_C(v)\, dv \tag{27}$$

where $f(v)$ is the Weibull probability distribution function (PDF), and P_C is the power curve of the examined wind turbine.

The Weibull PDF is defined as follows (Alavi *et al.* 2016b)

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{28}$$

where v is the wind speed. k and c are the shape and scale parameters, respectively, which are estimated using the maximum-likelihood estimation (MLE) method.

Table 22 The performance of the six different wind turbines installed in the station at Khaf

Turbine	Hub height	Rated power	Mean net power output	Mean net energy output	Net capacity	Hydrogen production
	(m)	(kW)	(kW)	(kWh/yr)	(%)	(Nm^3)
AREVA M5000	102	5,000	2,253.4	19,739,870	45.1	3,750,575.3
AWE 54	75	900	420.0	3,678,940	46.7	698,998.6
Bergey Excel-R	43	7.5	2.9	25,727	39.2	4,888.13
Bergey Excel-S	30	10	4.0	35,060	40.0	6,661.4
DeWind D8.2	80	2,000	925.8	8,110,320	46.3	1,540,960.8
Vestas V52	74	850	388.0	3,398,513	45.6	645,717.47

As mentioned earlier, the city of Khaf was selected as the most proper location for installing wind farms, and also hydrogen production. Six wind turbines with different sizes and hub heights are considered as case studies in this study. Table 22 lists the wind turbines' characteristics, the annual energy, and the amount of hydrogen production.

One important indicator for judging the performance of wind turbines is the net capacity factor. The net capacity factor is the ratio of actual wind power output to its rated power, and its larger value shows that the wind turbine performs better (Chang *et al.* 2003). As seen from Table 22, it is obvious that the AWE-54 wind turbine exhibits a greater performance than others, however, the AREVA M5000 will produce more mean net energy output because of its higher rated power, and consequently, its hydrogen production capability will be more than other ones. It is also evident that using the AREVA M5000 wind turbine will lead to the hydrogen production amount of 3.75×10^6 Nm^3 (or 337 ton), which is an enormous amount that can be used in transportation and other industries.

6. Conclusions

In this study, DEA method was used to analyze the gathered data in order to obtain a ranking for different cities or DMUs. The cities of Khorasan were first analyzed and ranked with help of BCC model in its both primary and secondary (dual or envelop) modes. BCC model results showed an efficiency level of 1 for nine of the ten cities, and the city of Rudab was the only city that was identified as inefficient. Given that the number of selected cities was less than three times the total number of inputs and outputs, some inefficient cities were placed on efficient frontier due to the lack of sufficient DMUs. This issue resulted in obtaining the efficiency level of 1 for most of the cities. To overcome this issue, super-efficiency method (Anderson-Peterson) was used to reevaluate the ranks of these cities. Results of Anderson-Peterson method, used in both of its primary and secondary (dual) modes, showed that city of Khaf with an efficiency of 2.21 ranked first, and city of Afriz with an efficiency of 0.72 was in the last place of this ranking, and cities of Ghadamgah, Fadashk, Sarakhs, Bojnoord, Nehbandan, Esfaraen and Davarzan with the efficiencies of 1.21, 1.17, 1.14, 1.049, 1.026, 1.02, and 1.01, were ranked second to ninth for the installation of wind turbines. Six different wind turbines from the range of 7.5 to 5,000 kW were used in the analysis for the station at Khaf. The results showed that the AWE-54 wind turbine performs better than other ones because of its higher capacity factor. However, the AREVA

M5000 will produce more electricity. Additionally, a stand-alone wind-to-hydrogen energy conversion system was considered in this study. The relationship between the amount of hydrogen production and the annual wind energy was linear so that the AREVA M5000 wind turbine produces a great amount of 337 ton-H_2 per year.

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