Using MCDM approaches to rank different locations for harnessing wind energy to produce hydrogen

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Abstract

Utilizing wind turbines to produce electricity has been increasing in recent years, due to technology advancement, global warming and environmental pollution. Identification of the most suitable place for harnessing wind energy is enormously important, so effective criteria must be considered. This study is aimed to prioritize different cities of Fars province for establishment wind farm facilities. In order to this purpose six major criteria including wind power density, topographic situation, distance to distribution net, population, land cost and natural disasters were investigated. Wind power as the foremost criterion, that a candidate site must have, is the high degree of continues and persistent windiness. The Weibull distribution function has been applied to estimate the wind power density by using 3-h wind speed and other meteorological data. The function's results indicated that Izadkhast has the most value of wind power with amount of 166.64 W/m^2. Data Envelopment Analysis (DEA) and Andersen-Petersen (AP) were used to rank the under study areas. FTOPSIS and AHP were applied for validating calculated results. Finally it is suggested that Izadkhast is the best city for wind-hydrogen conversion constructions. About 21.9 ton hydrogen will be produced per year by using a 900 kW wind turbine in the city.

Keywords
Data Envelopment Analysis (DEA), Andersen-Petersen (AP), Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS), Analytical Hierarchy Process (AHP),

1. Introduction

Nowadays, Ozone depletion, increasing global average temperature, climate change, different types of pollution, and high dependence on fossil fuels are some the major issues facing humanity. As is obvious, sources of coal, oil and gas will eventually end in a foreseeable future. So increased use of clean and renewable energies is one of the measures that many developed countries have taken in recent decades to somehow tackle these problems. Development of renewable energy technology and its side benefits such as reduced pollution, abundance and permanence have caused this type of energy, especially wind energy to become economically viable (Mostafaeipour et al. 2013) and to be viewed favorably by all experts on this subject. Wind energy, like other renewable energy sources, is geographically widespread and is almost always available but it is also dispersed and decentralized and has a fluctuating and intermittent nature (Azadeh et al. 2014).

So performing extensive research on this type of energy sources is obviously necessary. In this paper, we aim to prioritize and rank the cities of Fars province in terms of their suitability for the construction of a wind farm. All the factors influencing the issue must be considered to minimize the costs and to choose the right location; so after conducting some initial research about wind energy and factors influencing it, 6 criteria of wind conditions, topographical conditions, population, distance from distribution grid, land price, and probability of natural disasters were selected as effective factors (Mostafaeipour et al. 2014; Azadeh et al. 2011). In this research, we selected 13 different cities of Fars province including Izadkhast, Estahban, Eghlid, Shiraz, Fasa, Safashahr, Bavanat, Abadeh, Arsanjan, Kazerun, Neyriz, Sepidan and Firuzabadto rankthem in terms of suitability forwind turbine installation. AHP (Jovanovic et al. 2015) and FTOPSIS (Sang et al. 2015) are used to validate the results of DEA.

2. Geographical Profile

Fars province is located in south and southwest of Iran, between E50°36'- E55°35' longitude, and W27°03toW31°40' latitude; area of this province is 122000 km^2 which constitutes about 12.5 percent of Iran's total area and it is the fourth largest province in the country (Wikipedia.org). Figure 1 shows the map of Iran and location of the province and its cities.

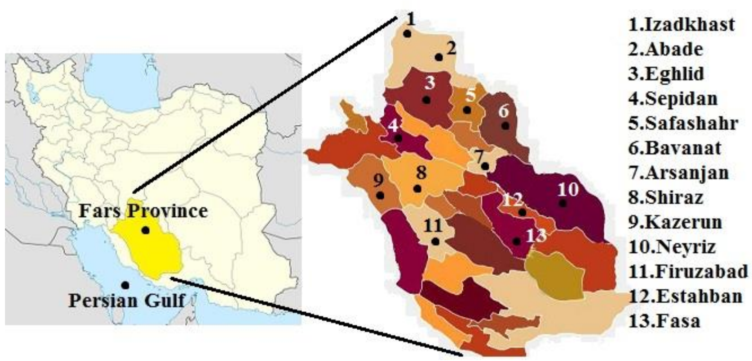

Figure 1: Map of Iran and cities of Fars province.

3. Methodology

In this study, DEA method and a set of economic, technical and geological factors are used to prioritize and rank 13 cities of Fars province in terms of their suitability for the construction of a wind farm. AHP and FTOPSIS are also used to assess the validity of obtained results.

One important application of DEA method is the prioritization and ranking of DMU's that do similar tasks, which is done by comparing the efficiency obtained for each DMU. In this study, relative efficiency of 13 cities in Fars province will be compared by considering 3 inputs and 3 outputs, and then this cities (DMU's) will be ranked in terms of their potential and suitability for the construction of wind farm.

There are 13 DMU's (cities) and 6 criteria in this study, so we will use the dual form of DEA method, which will be as follows (Mirjalili et al. 2010; Movahedi et al. 2010):

$$\mathrm{Min}\ Z_p = \theta \tag{1}$$

Subject to: $\sum_{j=1}^{n} l_j y_{rj} \geq y_{rp}$

$$\theta x_{ip} - \sum_{j=1}^{n} l_j x_{ij} \geq 0$$

$l_j \geq 0$
r = 1, 2, …,S
i= 1, 2, …, K
j = 1, 2, …, n

In this model, z_p is the efficiency of unit p, θ is the variable that should be minimized, Y_{rj} is the r^{th} output (r=1 to s)of j^{th} DMU(j=1 to n), X_{ij} is the i^{th} input (i=1 to k) of j^{th} DMU, and I_j*'s* are the coefficients that should be calculated for constraints. In the cases where this model again results in several efficient DMU's (several DMU's with the score of 1), comparing these efficient DMU's at that point will be impossible. Andersen-Petersen (AP) model can be used to tackle this problem. In AP model, efficiency value of efficient DMU's are allowed to be greater than 1. This is done by eliminating the p^{th} constraint in initial model or eliminating the p^{th} variable (weight) from the constraints of dual model, in each cycle of model. This model can be used for both basic form and dual form of DEA. Since we have used the dual form of DEA for initial prioritization, we should also use the dual form of AP model to rank the efficient DMU's. The following small changes will modify the dual model mentioned above by Andersen-Petersen method (Wanke and Barros, 2014):

$\mathrm{Min}\ Z_p = \theta$**Error! Bookmark not defined.** (2)

Subject to: $\sum_{\substack{j=1 \\ j \neq p}}^{n} l_j y_{rj} \geq y_{rp}$

$$\theta x_{ip} - \sum_{\substack{j=1 \\ j \neq p}}^{n} l_j x_{ij} \geq 0$$

$l_j \geq 0$
r = 1, 2, ...,S
i= 1, 2, ..., K
j = 1, 2, ..., n

The only difference between this model and the previous model is that p^{th} term will be removed from the constraints in each cycle of this model.

4. Analysis

4.1 Wind power

First and foremost condition that a candidate site for the construction of wind farm must have is the high degree of continues and persistent windiness. In this study, 3-hourly wind speed data, temperature and air pressure for a period of 10 years (2006 to 2015) was collected from national meteorological organization, and then equation 3 was used to extrapolate these data for the height of 40 meters (Mohammadi and Mostafaeipour, 2013).

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \quad (3)$$

Wind power density in each area can be calculated by equation 4 (Mohammadi et al., 2014).

$$\frac{P}{A} = \int_0^{\infty} \frac{1}{2} \rho v^3 f(v) dv = \frac{1}{2} \Gamma \rho c^3 \left(1 + \frac{3}{k}\right) \quad (4)$$

Two parameters of ρ(air density) and Γ(gamma) can be calculated by equations 5 and 6 respectively (Mostafaeipour et al. 2011).

$$\rho = \frac{\bar{P}}{R_d \bar{T}} \quad (5)$$

Γ (x) = $\int_0^{\infty} e^{-u} u^{x-1} du$**Error! Bookmark not defined.** (6)

In equation 4, two parameters of ***c*** and ***k*** are scale factor and shape factor that can be calculated by equations 7 and 8 respectively (Mirhosseini et al. 2011):

$$c = \frac{v}{\Gamma * \left(1 + \frac{1}{k}\right)} \quad (7)$$

$$k = 0.83 v^{0.5} \quad (8)$$

Ultimately, the mean wind power for each of the cities was calculated by Excel software; the results are presented in Table 1.

Table 1. Average of 10-years wind power of the 13 cities.

City	Wind power (W/m^2)
Izadkhast	166.64
Estahban	84.00
Safashahr	126.63
Firuzabad	60.40
Eghlid	74.72
Neyriz	56.06
Sepidan	65.26
Arsanjan	126.23
Bavanat	130.60
Abadeh	63.24
Fasa	27.86
Kazerun	45.64
Shiraz	26.40

4.2 Topographical conditions

Wind data collected from meteorological organization is only valid within a circle with a radius of 7.5 km centered at the weather station (Rezaei-Shouroki et al. 2017), so suitable areas for each city should be selected within this valid area, and urban regions and residential and industrial areas and areas with tree cover should also be removed. Area of suitable regions for the construction of wind farm was calculated with the help of experts on this subject. These regions and their area calculated for each city are presented in Table 2. In the best topographical conditions, which means an area without any tree cover, buildings, mountains and hills, the maximum value in Table 2 can be the area of a circle with a radius of 7.5 km that is 176.7 square kilometers. Between all the cities of the research Eghlid city has the most appropriate places with 171 km^2 and the worst city is Shiraz with 117 km^2.

Table 2. suitable area topographical.

City	Topographic situation (km^2)
Izadkhast	165
Estahban	155
Safashahr	168
Firuzabad	142
Eghlid	171
Neyriz	159
Sepidan	112
Arsanjan	132
Bavanat	141
Abadeh	165
Fasa	147
Kazerun	137
Shiraz	117

4.3 Distance from power distribution grid

Table 3 shows the average distance of topographically suitable locations (at least 20 sites for each city) from 20 kV substations within each city. For each city, first the topographically suitable locations are selected and then the average distance of these locations from the center of the city are considered as the value representing the criterion of distance from power distribution grid.

Table 3. Average of distances to distribution net.

City	Distance to distribution net (km)
Izadkhast	6.61

Estahban	6.73
Safashahr	6.77
Firuzabad	6.10
Eghlid	6.83
Neyriz	6.85
Sepidan	4.35
Arsanjan	5.17
Bavanat	5.22
Abadeh	6.52
Fasa	6.53
Kazerun	4.95
Shiraz	4.40

4.4 Land price

Regions suitable for wind farm are located outside residential areas so the average price of agricultural land is considered for this criterion. These values are presented in Table 4.

Table 4. Land cost.

City	Land cost (Rial/m^2)
Izadkhast	650000
Estahban	650000
Safashahr	1100000
Firuzabad	1900000
Eghlid	950000
Neyriz	1750000
Sepidan	1050000
Arsanjan	700000
Bavanat	800000
Abadeh	1000000
Fasa	900000
Kazerun	1300000
Shiraz	4500000

4.5 Natural Disasters

The probability of 3 natural disasters of flood, earthquake, and dust storm are considered for this criterion, because they impose the risk of damaging or even destroying wind turbines. So wind farm should be constructed in a location that has the minimum probability of such events. The number of recorded floods by the end of 2013 for a period of about 62 years is considered for calculating the flood sub criteria (more data are not available). Therefore, Poisson distribution was used to calculate the probability of at least one flood in 25 years lifespan of turbine (Rezaei et al. 2017). Table 5 shows the flood statistics for each city and the calculations performed to obtain the probability of flooding.

Table 5. Number of floods, Landa Poisson and Poisson distribution.

City	Number of floods (for 62 years)	Landa Poisoon (for 25 years)	Poisson distribution of floods
Izadkhast	5	2.016	0.816
Estahban	6	2.419	0.911
Safashahr	5	2.016	0.867
Firuzabad	7	2.823	0.941
Eghlid	5	2.016	0.867
Neyriz	6	2.419	0.911
Sepidan	6	2.419	0.911
Arsanjan	3	1.210	0.702
Bavanat	2	0.806	0.554

Abadeh	5	2.016	0.867
Fasa	4	1.613	0.801
Kazerun	4	1.613	0.801
Shiraz	4	1.613	0.801

According to statistics related to earthquakes, the number of recorded earthquakes in different cities of Fars province belongs to a 100 year period. In this case, there was no record of destructive earthquakes that can damage wind turbines (8 and higher on the Richter scale (www.SUNA.org.ir) in any of these areas, so the probability of destructive earthquake was considered zero for all these cities.

The number of events related to dust storms category is high, so Poisson distribution cannot be used. In this case, given the high number of trials (number of studied days) we used Binomial distribution with normal approximation. This approximation involves calculating the probability of success (***p***) and the number of trials (***n***) for Binomial distribution, and then calculating the mean (μ) and standard deviation (σ) of normal distribution by equations 9 and 10 and ultimately calculating the probability of at least 1 event by normal distribution.

$$(9)\mu = np$$

$$(10)\sigma^2 = np(1-p)$$

In here, ***n*** is the number of days which means the number of days in normal lifespan of a turbine (25 years), so it is 9131 days. Then the probability of at least one dust storm in a period of 25 years must be calculated. Table 6 shows the statistics of this event for each city and calculations of variables ***p*** (the probability of dust storm in a day in Binomial distribution), and ***n*** (the number of studied days or number of trials in Binomial distribution), normal μ and σ and ultimately the probability of at least 1 such event.

Table 6. Binomial distribution parameters and probability of dust storm occurrence.

City	p	n=9131 (25×365+6)	μ=np	σ	Probability of at least once dust storm and normal distribution
Izadkhast	0.08	9131	750.49	26.245	0.86
Estahban	0.11	9131	1000.66	29.85	0.87
Safashahr	0.07	9131	675.44	25	0.86
Firuzabad	0.06	9131	525.35	22.25	0.86
Eghlid	0.14	9131	1250.82	32.85	0.88
Neyriz	0.15	9131	1325.87	33.66	0.88
Sepidan	0.03	9131	300.20	17.04	0.85
Arsanjan	0.003	9131	25.02	4.99	0.84
Bavanat	0.07	9131	625.41	24.14	0.86
Abadeh	0.11	9131	1000.66	29.85	0.87
Fasa	0.09	9131	825.54	27.4	0.86
Kazerun	0.06	9131	525.35	22.25	0.86
Shiraz	0.21	9131	1951.28	39.17	0.90

The final step is to combine the probabilities of these three natural disasters, so that we can obtain a value that can represent this criterion in the model. Thus, according to expert's opinion, weight coefficient of 0.25, 0.25, and 0.5 were considered for flood, earthquake and dust storm respectively, and results are presented in Table 7.

Table 7. Probability of once occurrence of natural disasters in 25 years.

City	Earthquake	Flood	Dust storm	Probability of natural disaster (at least one time in 25 years)
Izadkhast	0	0.816	0.86	0.647
Estahban	0	0.911	0.87	0.663
Safashahr	0	0.867	0.86	0.647
Firuzabad	0	0.941	0.86	0.665
Eghlid	0	0.867	0.88	0.657
Neyriz	0	0.911	0.88	0.668
Sepidan	0	0.911	0.85	0.653
Arsanjan	0	0.702	0.84	0.596

Bavanat	0	0.554	0.86	0.569
Abadeh	0	0.867	0.87	0.652
Fasa	0	0.801	0.86	0.630
Kazerun	0	0.801	0.86	0.630
Shiraz	0	0.801	0.90	0.650

4.6 Population

Another important criterion for the location of wind farm is population. It is obvious that this factor should be considered as an output of DEA model, because higher population means that area is more preferable for the installation of wind turbine. Table 8 shows the population of the cities.

Table 8. Population of the cities (Wikipedia.org).

City	Population (person)
Izadkhast	27800
Estahban	66172
Safashahr	50252
Firuzabad	119721
Eghlid	98188
Neyriz	113750
Sepidan	89398
Arsanjan	41476
Bavanat	48416
Abadeh	93975
Fasa	200000
Kazerun	320792
Shiraz	1700678

5. Discussion

AHP and FTOPSIS are applied to verify the results of DEA method. According to the results of three ranking methods, city of Izadkhast is the best option for the construction of wind farm, because it holds the top rank in validity assessment methods and second rank in DEA method. Therefore, changes in the ranking of Izadkhast are very low which shows the stability and reliability of its rank. Results of ranking by the MCDM approaches are shown in table 9.

Table 9. Results of the 3 ranking methods.

City	Ranking with DEA	Ranking with AHP	Ranking with FTOPSIS
Izadkhast	2	1	1
Estahban	5	6	5
Safashahr	8	2	4
Firuzabad	13	8	13
Eghlid	7	7	6
Neyriz	12	9	12
Sepidan	11	11	9
Arsanjan	10	4	3
Bavanat	3	3	2
Abadeh	9	10	8
Fasa	4	13	11
Kazerun	6	12	10
Shiraz	1	5	7

In this study, a rectifier with the efficiency of 95% and an electrolyzer with the energy consumption of 5 kWh/Nm3 were considered. Also, a coefficient for converting H_2-Nm^3 to H^2-ton should be considered in the analysis. A wind turbine of AWE 54-900 kW, manufactured by Americas Wind Energy Inc., is selected for the evaluations. The city of Izadkhast was selected as the most appropriate location to generate wind energy. The best capacity factor of this wind turbine is related to the year of 2006 with the value of 18.9%.

6. Conclusion

The most important findings of this study can be summarized as follows:

- For ranking the cities, 6 important criteria including 3 output criteria of wind conditions, topographical conditions, and population and 3 input criteria of distance from distribution grid, land price, and probability of natural disasters were used for DEA model.
- The probability of 3 natural disasters of flood, earthquake, and dust storm were considered for this criterion as sub criteria, because they impose the risk of damaging or even destroying wind turbines. According to expert's opinion, weight coefficient of 0.25, 0.25, and 0.5 were considered for flood, earthquake and dust storm respectively
- For Bavanat and Neyriz were calculated the least (0.569) and the most (0.668) probability of natural disaster, respectively.
- Weibull distribution was used for calculation of wind power density. Finally specified that Izadkhast city has the most value of wind power between the other cities (with value of 166.64 W/m^2). Because wind power had given a "very important" preferential value in 2 validations method so Izadkhast were placed in top of the 13 cities with AHP and FTOPSIS.
- After ignoring places with trees, hills, mountains and tall building, Safashahr was specified as the best city in terms of topographic situation with 171 km^2 suitable lands, versus Shiraz was detected as the worst city with 117 km^2 suitable lands.
- Average of suitable distances to the city center in circle with 7.5 km radius for Neyriz was calculated 6.85 km so this city has most distance and versus Shiraz has least distance to distribution net.
- After executing DEA model, rank of 5 cities were specified but 8 cities including Izadkhast, Estahban, Safashahr, Eghlid, Bavanat, Fasa, Kazerun and Shiraz have obtained full efficiency score, so for ranking these cities is used from AP model.
- Final rank of the cities by usage of DEA was 1- Shiraz, 2- Izadkhast, 3- Bavanat, 4- Fasa, 5- Estahban, 6- Kazerun, 7- Eghlid, 8- Safashahr, 9- Abadeh, 10- Arsanjan, 11- Sepidan, 12- Neyriz and 13- Firuzabad.
- After ranking the cities with 2 validation methods, Izadkhast city was recommended to wind farm establishment.
- The utilizing a wind-hydrogen energy conversion system will result in a substantial amount of hydrogen production (averagely 21.9 ton/year) when a 900 kW wind turbine is installed in this location.

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