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RESEARCH ARTICLE

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Feasibility of using wind turbines for renewable hydrogen production in Firuzkuh, Iran

Abstract The present study was conducted with the objective of evaluating several proposed turbines from 25 kW to 1.65 MW in order to select the appropriate turbine for electricity and hydrogen production in Firuzkuh area using the decision making trial and evaluation (DEMATEL) and data envelopment analysis (DEA) methods. Initially, five important factors in selection of the best wind turbine for wind farm construction were determined using the DEMATEL technique. Then, technical-economic feasibility was performed for each of the eight proposed turbines using the HOMER software, and the performance score for each proposed wind turbine was obtained. The results show that the GE 1.5sl model wind turbine is suitable for wind farm construction. The turbine can generate 5515.325 MW of electricity annually, which is equivalent to $ 1103065. The average annual hydrogen production would be 1014 kg for Firuzkuh by using the GE 1.5sl model turbine.

Keywords wind turbine, hydrogen production, HOMER software, decision making trial and evaluation (DEMATEL), data envelopment analysis (DEA), Firuzkuh

1 Introduction

Global environmental concerns and the need to use energy along with the sustainable progress in the field of renewable energy technologies have led to creation of new types of renewable energy sources for public use [1]. Among renewable energy sources, wind power has had a faster growth than other renewable sources, because the use of wind turbine leads distributed generation system to a system with variable production in addition to the environmental and economic capabilities in production of clean and sustainable energy [2]. On the other hand, the biggest problem in the use of wind energy is the variability of wind speed and subsequently the production capability of wind turbines [3]. Based on this fact, the selection of proper turbine and combination of wind turbines with other energy sources will increase the reliability of energy production system and make output electrical power to be almost independent of time [4]. In this regard, numerous studies have been conducted in different aspects to solve the problem of selecting the right turbine for construction of wind or combined power plant. Chawdhury et al. [5] have tried to select appropriate turbines for wind farms using unrestricted wind farm layout optimization (UWFLO). Constant wind conditions (wind speed and direction) and constant type of selected turbine for the wind farm are necessary conditions in order to be used in the selection of suitable wind turbine. Montoya et al. [4] have used multifactorial evolutionary algorithms such as multifactorial genetics (NSGAII) colonial algorithm such as SPEA2, PESA and msPEA to select the appropriate turbine by using wind speed data and the power output of the turbine in which the results of the PESA algorithm is slightly better than the results of three other algorithms. Ritter and Deckert [6] have used wind energy index including long-term data of wind speed in several parts of southern Germany to select wind turbine based on the amount of electricity generated by each turbine. Perkin et al. [7] have proposed a combined method of the blade element momentum theory, the multiple evolutionary computing algorithms, and a realistic cost model to select the appropriate turbine in Burfell of Iceland. The data used are wind speed and the amount of output per turbine. Hammad and Betarseh [8] have tried to select the appropriate turbine in Jordan region using the Weibull distribution function, the wind speed, and the amount of electricity produced using proposed wind turbines. Salem

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[9] has used wind speed and the wind energy potential data obtained from the Weibull function in Al-Fattaih-Derna area in Libya to select the appropriate turbine to set up wind power plant.

Today, the rapid increase of energy demand has led to more sustained attention to efficient use of new energy sources [10]. So, hydrogen consumption increases significantly as an energy source [11]. Hydrogen can be the product of different energy generation processes from a diverse set of sources such as coal, oil, natural gas, and geothermal, biomass, nuclear and renewable energies, associated with their own requirements and technologies [12,13]. There are currently four industrial methods for producing hydrogen, which include natural gas, oil processing, coal gasification, and electrolysis [14]. In the electrolysis, electrical energy is used to separate hydrogen molecules from water molecules. The amount of power consumed in this procedure is about 6.7–7.3 kWh/Nm^3 and the efficiency of industrial scale production of hydrogen through this system has been reported to be approximately 50%–55% [15].

One of the important benefits of hydrogen production through electrolysis is that it makes it possible to use clean and environmentally friendly methods for producing the power required for the process. Therefore, hydrogen production systems operating based on renewable energy sources (such as wind farms) have been the subject of extensive research [16]. Figure 1 shows the diagram of the wind-hydrogen plant.

Patyk et al. [17] have studied hydrogen production from the process of high temperature electrolysis through water, wind and nuclear power plants. According to this study, the use of wind energy for hydrogen production leads to a 21%–41% decrease in CO_2 emission. Besides, using alkaline electrolysis decreases the CO_2 emission by 72%–80%.

Siyal et al. [18] have studied hydrogen production using the proton exchange membrane (PEM) method in Switzerland. According to this study, wind energy can be used to produce 25580 kt of hydrogen per year, which is equal to 860 TWh of energy. It is also reported that using hydrogen fuel decreases CO_2 emission by 50%.

Moreover, Giddey et al. [19] have investigated the effect of carbon on the water electrolysis process for hydrogen production. It is reported that the use of carbon decreases the power consumption of the electrolysis process by 40% and that the remaining 60% can be compensated by the chemical energy of carbon.

In another research, Suleman et al. [20] have examined the environmental impacts of different methods for hydrogen production. It is found that although the steam methane reforming method has the highest efficiency in hydrogen production. It produces 12 kg of CO_2 emissions, which is the greatest amount of greenhouse gas emissions of the methods assessed. In addition, the solar-based and wind-based hydrogen production methods are found to produce the least amount of CO_2 emissions, i.e. 0.37 kg and 0.325 kg, in that order. According to this study, hydrogen production through renewable energies has the least amount of environmental impacts.

Huang et al. [21] have used a PV cell-wind turbine hybrid system to produce the power required for hydrogen production through electrolysis. They measured the amount of hydrogen production at temperatures of 20°C, 60°C, and 80°C. According to this study, two scenarios lead to increased efficiency of hydrogen production system: ① when 12 MW of power is supplied by the wind turbine and the remaining 18 MW is supplied

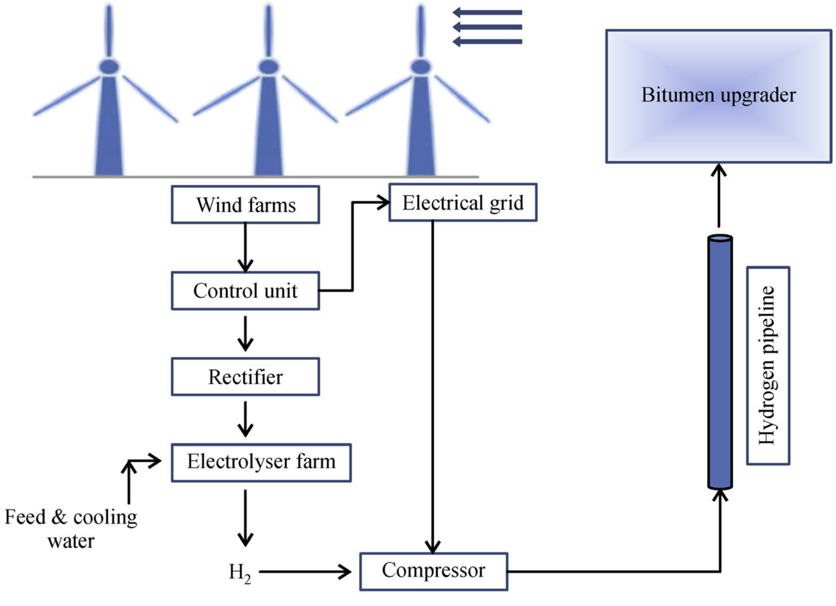


Fig. 1 Schematic diagram of the wind-hydrogen plant [16]

by the PV cell. ② when the temperature of the electrolyzer reaches 60°C, which improves the system performance by 0.1% as compared to a temperature of 40°C.

Mostafaeipour et al. [22] have also studied the feasibility of hydrogen production with the use of wind turbines. They have assessed the feasibility of energy generation through wind turbines in four cities of Shiraz and found that Abadeh has the best conditions for hydrogen production through wind energy. The annual electricity output of one analyzed turbine is found to be 575.53 MWh which can provide a hydrogen consumption of 22 cars for one week.

In addition, the feasibility of hydrogen production through wind energy in Cordoba, Argentina has been examined by Sigal et al. [23]. According to their study, the region with the highest potential for hydrogen production is Rio Cuarto, where 21 t of hydrogen can be produced annually for each 5 MW of energy produced by wind turbine. The cost of hydrogen production is estimated to be about 9.41 \$/kg H_2 which is twice the cost of liquid fuel in Cordoba.

Olateju et al. [16] have investigated the feasibility and cost of hydrogen production through wind farms with a capacity of 563 MW in Alberta, Canada. It is reported that the minimum cost of hydrogen production is 9.00 \$/kg H_2, of which 63% arise from side expenditures of the power plant. Therefore, the cost of hydrogen production through electrolysis is actually 3.37 \$/kg H_2.

Also, a study on the feasibility of production and storage of hydrogen through wind energy in Pays de la loire, France has found that given the relatively low cost of fossil fuels in France and high initial cost of construction and operation of wind power plants, hydrogen production through wind energy will have no economic justification. The cost of hydrogen production through gas is reported to be around 4.2 €/kg H_2 while the cost of hydrogen production through wind farms is found to be around 47 €/kg H_2 [24]. Clearly, numerous studies related to renewable energies have been conducted in Iran which indicate the feasibility of implementing this source of clean energy in many parts of Iran [25–30].

The major methods for selection of the appropriate turbine in order to set up a wind power plant or a combined power plant using wind energy depend on the characteristics of wind speed and the output of desired turbines. Although simulations have also been conducted in these researches, it seems that characteristics such as wind speed in the area studied, the amount of electricity generated by each proposed turbine, the revenue, the cost of wind power systems, and the pollution caused by it should be simulated first to select the appropriate turbine for construction of wind power plants or combined power plants containing wind energy and then the process of selecting the appropriate turbine should be considered as influential factors. In addition, it is necessary to conduct technical-economic simulations of each turbine in one convenient application. Accordingly, this gap has been observed in previous researches and attempts have been made to initially identify factors affecting turbines selection for wind power plants or combined power plants which include wind power and the selection of the appropriate turbine using the values of these factors.

2 Geographic characteristics

Firuzkuh, a city in Tehran, is the capital of Firuzkuh County, Tehran Province, Iran with a latitude of 35°45′25″N and a longitude of 52°46′26″E ordinarily. At the 2006 census, it had a population of 15807, in 4334 families. It is located north-east of Tehran, in the middle of Alborz Mountains. Previously, it was part of Mazandaran Province[1)]. It has a relatively cool and windy climate and some natural attractions including TangeVashi, Boornic Cave, Roodafshan Cave, GardaneGadook and sight-seeing of villages like Varse-Kharan, Zarrin Dasht, Darreh-Deh, and Kaveh-Deh. Firuzkuh is rich in historical heritage and some of the most ancient objects in Tehran Province have been found there. Of these villages, Darreh-Deh contains the most ancient places. During the reign of Timur, Ruy Gonzalez de Clavijo praised a nearby concentriccitadel and suggested that it could resist any assault. Veresk Bridge lies on the road north from Firuzkuh[2)]. Figure 2 illustrates Iran’s map including the place for the case study.

Fig. 2 Map of Iran showing Firuzkuh area

[1)] Available at firoozkooh.farhang.gov.ir website, Accessed Apr. 4, 2016 (in Farsi).

[2)] Firuzkuh, Iran. 2016–04–08, available at wikipedia.org website

3 Methodology

3.1 Decision making trial and evaluation (DEMATEL) technique

The DEMATEL technique was used in the late 1971 mainly for global complex problems and the judgment of experts in the fields of scientific, political, economic, social and religious leaders and artists [31]. Three different types of questions are used in this technique: questions concerning the characteristics and influencing factors of a given issue, questions about possible relations of factors by determining the severity of relations in term of Cardinal, and question for the evaluation of the detected elements' nature and criticizing them for possible re-evaluation of the implementation of this method. Effective factors in a problem and possible relations and effectiveness severity of relations between factors are determined by numerical evaluation [32]. In a way that structuring factors obtained from expert's opinion or factors extracted from the thematic literature provides the possibility of understanding relations and ultimately the importance of factors for experts [33]. Decision-making based on paired comparisons and accepting the feedback of relations are among superiorities of the DEMATEL method to other methods. This means that each element can affect all elements of its level and be affected by each of them in its hierarchical structure [34]. Acceptance of transferable relations and the ability to view all possible feedbacks are also among the superiorities of this method compared to other methods [35].

This technique has 9 basic steps as follows [36]:

1) Determining the elements constituting the system using methods such as brainstorming, and Delphi.

2) Forming the survey matrix and providing them to experts in order to identify the intensity of effects by scoring.

3) Collecting the resulting matrix of the previous step and deciding on the presence or absence of the relationship between the two factors by majority vote.

4) Calculating the median of scores to show direct relation of the effect of factors for each of the confirmed relations in the previous step.

5) Forming $\boldsymbol{X}$ matrix with respect to the third and fourth steps.

6) Calculating the row sum of $\boldsymbol{X}$ matrix elements and multiplying it by inverse of the maximum amount. This will provide the relative effect intensity of direct relations in the system ($\boldsymbol{M}$).

7) Calculating $\boldsymbol{S}$ matrix using $\boldsymbol{S} = \boldsymbol{M}(1–\boldsymbol{M})^{-1}$ equation which shows the relative effect intensity of direct and indirect relations.

8) Row sum of element (R), columnar sum of elements (J) and total ($R + J$) and subtraction ($J–R$) are calculated for $\boldsymbol{S}$ matrix.

9) Determining the hierarchy of elements.

There are two main reasons for implementing the DEMATEL technique to determine the key factors in selecting appropriate turbine to produce electricity and hydrogen:

1) This technique has a great ability in structuring complex problems in the form of groups of cause and effect, and in consideration of the factors studied interoperability.

2) This technique allows the researcher to better understand the relationship between factors, and the status of them.

3.2 Data envelopment analysis (DEA) model

The DEA model, which is a nonparametric model, is used to estimate the degree of efficiency grading. DEA models can be input-oriented or output-oriented and are specified in form of constant returns to scale (CRS) or variable returns to scale (VRS) [37]. In addition, output models will make maximum output with regard to the values of the input factors while input models will make minimum input with regard to the levels of the output factors [38]. DEA covers all data, figures, and information, which is the reason for being called DEA. It should be mentioned that there is no need to have determined type of function (Cobb-Douglas, translog, etc.) in the DEA method in measuring efficiency [39].

The measurement of efficiency started from Farrell's study which was based on works done by researchers such as Debreu and Koymanz. Charnes, Cooper, and Rhodes (CCR) who provided their model based on minimizing production factors and with assumption of CRS which had the ability to measure efficiency with several inputs and outputs. The proposed method was in both input and output oriented modes [40]. The DEA method was obtained in 1984 with regard to VRS assumed by bunker, Charnes Cooper (BCC) to measure the efficiency. So, the input and output oriented models of this model are expressed as follows [41]:

$$\mathrm{Min}\theta, \tag{1}$$

$$\text{s. t.}$$

$$\sum_{j=1}^{n} \lambda_j \boldsymbol{y}_{rj} \geqslant \boldsymbol{y}_{r0}, \quad r = 1, 2, ..., s, \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j \boldsymbol{x}_{ij} \leqslant \theta \boldsymbol{x}_{r0}, \quad i = 1, 2, ..., m, \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j = 1, \tag{4}$$

$$\lambda_j \geqslant 0, \; j = 1, 2, ..., m, \tag{5}$$

where $\boldsymbol{x}_{ij}$ = input vector, $\boldsymbol{y}_{rj}$ = output vector, λ_j = weights, and θ = efficiency amounts.

This model shows the reduction ratio of the inputs studied to improve the efficiency. A unit is efficient in this model if and only if the following two conditions are met:

1) $\theta^* = 1$.

2) All of the auxiliary variables have the value of zero. The projects are ranked after calculating their efficiency. In this way the efficient projects are ranked and the one which are selected more as reference will be higher in rank [42].

Thus, the steps of this study are as follows:

1) Studying the parameters related to wind energy including wind speed, wind direction and altitude above sea level for the area studied.

2) Collecting data needed to conduct technical-economic feasibility of each of the proposed turbines in the HOMER software.

3) Analyzing the technical-economic feasibility of each of the turbines proposed and extracting the outputs of the HOMER software.

4) Selecting important factors for the ratings by using experts' opinions and weighting each factor using the DEMATEL technique.

5) Extracting efficiency score for each factor using the BCC model in Matlab software.

6) Determining the efficiency score for each proposed turbines using averaging of factors determined in the fourth step.

7) Carrying out rankings and determining the most economical and technical turbine in comparison with other evaluated turbines for power plant construction.

8) Providing presentation and interpreting technical-economic outputs obtained from the HOMER software for the proposed turbine, which includes tables, figures and financial calculations.

4 Analysis

4.1 DEMATEL analysis

To evaluate the factors and select the most important factor influencing the selection of economic and technical turbine for the construction of wind power plants, the factors were initially identified and ranked using the DEMATEL technique. This method determines the existing affecting factors in an issue and possible relations and the intensity of the effectiveness of relations between factors as a numerical score in a way that the possibility of understanding relations, feedbacks and ultimately, the importance of factors are provided for the experts by giving structure to the factors obtained from their opinions [43]. A list of available and effective factors in the analysis must be extracted in the first step using methods such as surveys of experts and studying existing literature, and etc. The identified factors which are considered as the main factors influencing the selection of suitable turbine for construction of power plant using the evaluations conducted are listed in Table 1.

Table 1 Suggested factors for evaluation of a wind power system

Factor number	Factor	Unit
1	Total cost[1]	$
2	Income	$/a
3	Wind turbines production	kWh/a
4	Total electric production	kWh/a
5	Grid sales	kWh/a
6	Pollution	kg/a
7	Capitals	$
8	Salvage	$
9	Turbine type	kW
10	Generator's type	kW
11	Convertor's type	kW
12	O&M cost	$/a
13	Replacement's cost	$
14	Interest rate	%
15	Generator's electric production	kWh/a
16	Battery type	W
17	Wind recourse	m/s
18	Fuel price	$
19	Operating cost	$

Note: [1]Total cost: including capital, O&M, replacement, fuel and salvage.

The results listed in Table 2 are obtained using Table 1. According to the DEMATEL technique, the amount of the impact of each factor on other factors with the acronym I (which is obtained by summing up the values of each row), and the amount of the impact of each factor on other factors is taken with the acronym R (which is derived from the sum of the values of each column). Therefore, the horizontal vector $\mathrm{I}+\mathrm{R}$ is the amount of influence and impact of the factors in the system, and the higher the value, the more interaction they have with other system factors. Besides, the vertical vector $\mathrm{I}+\mathrm{R}$ shows the strength of each factors' influence, and if it is positive, the factor is effective and, if negative, it is an impressive factor. Therefore, according to Table 2, the factors of total cost, income, wind turbines production, total electric production, grid sales, pollution, capitals, and salvage value were 1.428, 1.388, 1.269, 1.143, 1.067, 1.011, 0.982, and 0.855 respectively which are effective factors. The remaining factors are obtained as impressive factors.

Table 2 illustrates that the maximum impact on the total cost is equal to 4.321 and the least impact is equal to 0.969 which are related to operating costs.

Thus, according to Pareto's Law, 20% of the factors that have a high $R+J$ are used as the most important factors in selecting suitable turbine for construction of a power plant using ranking with the BCC method which is among common ranking methods of DEA. Thus, five factors including the electricity generated by the turbine, proceeds from each plant, the cost of construction of the new power plant, the sales numbers of the wind power grid, and the total generated electricity of each plant along with obtained values are used for each factor through technical-economic feasibility of each turbine in the HOMER software for ranking using the BCC method.

4.2 HOMER software outputs

The technical-economic feasibility of each turbine proposed is initially analyzed using the HOMER software and the results are presented in Table 3. Figure 3 illustrates the average wind speed obtained from the HOMER software.

Table 3 tabulates the wind turbine models selected by using the HOMER software, including the production capacity and the power generation of each turbine, the total generated electricity, the cost of construction of each plant, the number of used turbines in the simulation, the annual income, and the sales numbers of the wind power grid of each power plant.

As can be seen in Table 3, different models of wind turbines are analyzed for hydrogen production.

Besides the main purpose of this study which is selecting the suitable turbines to produce electricity and hydrogen on a large scale, the production capacity of small wind turbines for home use and agriculture household are also assessed.

However, turbines with powers of more than 1.650 MW are not investigated due to inadequate technical-economic terms in the area studied. The financial and technical details of the proposed turbines are also summarized in Table 3.

Table 2 Results obtained from the DEMATEL technique for each suggested factor in Table 1

Factor number	Ordinated factor	*R* + *J*	Factor number	Ordinated factor	*R*–*J*
Total cost	3	4.321	1	5	1.428
Income	2	4.120	2	8	1.388
Wind turbines production	1	3.972	3	4	1.269
Total electric production	6	3.689	4	7	1.143
Grid sales	4	3.508	5	6	1.067
Pollution	5	3.380	6	15	1.011
Capitals	7	2.712	7	13	0.982
Salvage	8	2.546	8	12	0.855
Turbine type	17	2.508	9	19	–0.994
Generator’s type	9	2.252	10	18	–1.263
Convertor’s type	14	2.098	11	14	–1.687
O&M cost	11	1.910	12	10	–1.461
Replacement’s cost	16	1.733	13	16	–1.712
Interest rate	10	1.528	14	9	–1.834
Generator’s electric production	15	1.487	15	17	–1.990
Battery type	12	1.258	16	11	–2.057
Wind recourse	13	1.321	17	1	–2.215
Fuel price	19	1.019	18	2	–2.374
Operating cost	18	0.969	19	3	–2.416

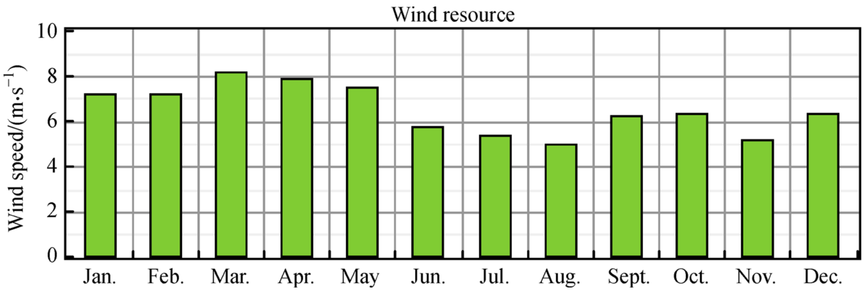


Fig. 3 Monthly average wind speed

4.3 Ranking

The DEA technique was used to rank the turbines proposed and simulated in the HOMER software. Since this technique has several methods for evaluating inputs and outputs, the BCC method which is an input-oriented method of the DEA technique is used due to the input orientation of the present study. For ranking, the code related to the BCC method was initially implemented in Matlab version R2014a. Then, the level of performance was obtained for each of the factors studied and the ranking between the 8 turbines proposed was conducted using the average performance score of all factors for each turbine proposed. Table 4 lists the results obtained from the ranking of the turbines proposed for determination of the best turbine for construction of the wind power plant in Firuzkuh.

According to the information on the performance of each turbine proposed in Table 4, the GE 1.5sl turbine with the highest performance is selected as the appropriate turbine for the wind power plant in Firuzkuh. Besides, it is clearly observed from Table 4 that the construction of a wind power plant using turbines with a high capacity has a better result than using small turbines. But the findings show that the GE 1.5sl wind turbine is suitable.

4.4 Techno-economic feasibility of selected wind turbine

According to the ranking conducted in Sub-section 3.3, the GE 1.5sl turbine was selected as the suitable turbine for construction of the wind power plant in the area studied. The technical-economic feasibility of this turbine is analyzed to produce hydrogen in the process of wind power plant in addition to providing the outputs of the HOMER software. Figure 4 depicts the output of the GE 1.5sl turbine for each hour of the day and in different months of the year as a D-map.

The color bar in the right side of Fig. 4 shows the status of electricity production at different times of the day and for different months. For example, between the hours of 12 and 18 in January, the output power of turbine is more than 1260.

Figure 5 shows the average monthly production of electricity of the GE 1.5sl turbine obtained from the

Table 3 Wind power production and revenue of each power plant

Turbine model	Rated power/kW	Turbine electric production / (MWh $\cdot$ a^{-1})	Total electric production /(MW $\cdot$ a^{-1})	Total costs/$	No. of turbines	Revenue /($ $\cdot$ a^{-1})	Grid sales /(kWh $\cdot$ a^{-1})
PGE 20/25	25	1380.583	1383.729	280787	12	276717	1352702
Integrity ew 15	50	162.197	170.312	50066	1	34063	139287
NW 100/19	100	328.484	3281.708	620787	12	636542	3227033
WES 30	250	8527.166	8530.157	1280787	12	1706032	5056364
Enercon E33	330	13256.261	13257.411	1680787	12	2651483	5993194
WWD-1	1000	13078.079	13080.468	3404700	4	2616094	5836679
GE 1.5sl	1500	5512.997	5515.325	1650273	1	1103065	4732391
Vestas V82	1650	5858.232	5860.768	1820219	1	1172154	4830158

Table 4 Ranking of nominated turbines

Turbine type/kW	Turbine electric production	Total electric production	Total costs	Incomes	Grid sales	Average	Ranking
PGE 20/25	0.8018	0.9017	0.8806	0.8318	0.7026	0.8237	8
Integrity ew 15	0.8659	0.8654	0.8045	0.9063	0.7149	0.8314	7
NW 100/19	0.8539	0.9253	0.8241	0.9866	0.8923	0.8964	5
WES 30	0.8588	0.9358	0.8422	0.8898	0.8760	0.8805	6
Enercon E33	0.9178	0.9409	0.8551	0.9038	0.8815	0.8998	4
WWD-1	0.9734	0.9663	0.9162	0.9529	0.8353	0.9288	3
GE 1.5sl	0.9721	0.9911	0.9389	0.9632	0.9049	0.9540	1
Vestas V82	0.9837	0.9633	0.9239	0.9448	0.8892	0.9410	2
Min	0.8018	0.8654	0.8045	0.8318	0.7026	0.8237	–
Max	0.9837	0.9911	0.9389	0.9632	0.9049	0.9540	–
Average	0.90343	0.9363	0.8732	0.8371	0.8945	0.8945	–

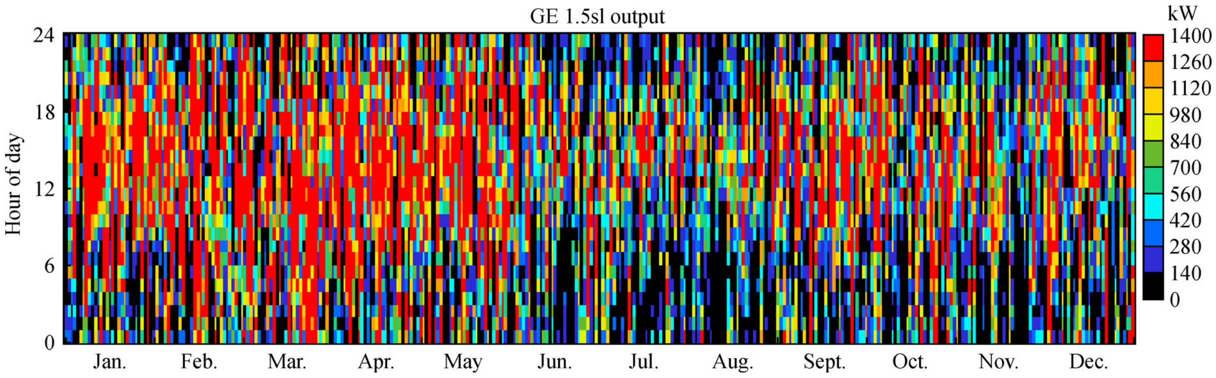


Fig. 4 Output of GE 1.5sl turbine for each hour of the day and in different months of the year as a D-map

HOMER software. This turbine has an output of 1320 kW in its highest level in February to March as the average monthly output. It also has its lowest production level in November and August with an average output of 1130 kW.

The average monthly power sold to the grid from the GE 1.5sl turbine obtained from the HOMER software is illustrated in Fig. 6.

Figure 7 shows the average monthly unsold electricity and grid surplus. According to Fig. 7, March to May have the highest level of grid surplus with a monthly average of 290 kW of unsold electricity and grid surplus. On the contrary, August and November have the lowest level of grid surplus with a monthly average of 180 kW of unsold electricity and grid surplus.

Table 5 tabulates the information related to the power grid for the proposed turbine. The information related to selling, buying, and the amount of surplus electricity can also be found in Table 4.

The simulation related to technical-economic feasibility of the wind power plant with a hydrogen system was conducted after describing the outputs related to the wind power plant for the GE 1.5sl wind turbine model. To simulate the wind-hydrogen system in the HOMER software, the same procedure for simulating a wind power is initially embedded. Then, a reformer, a hydrogen tank, an electrolyzer, and the amount of hydrogen loaded are selected in the HOMER software and the data related to the hydrogen system including costs, sensitivity analysis options, and hydrogen loaded are input into the software. The financial data are downloaded from reputable sites and the data loaded are downloaded directly from the official website of HOMER. Then, the processing is done by using

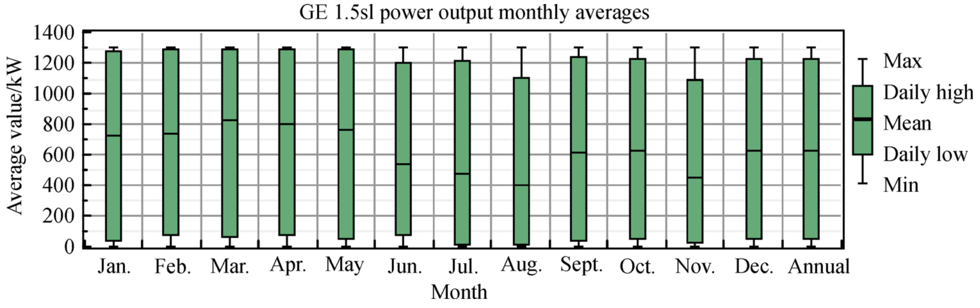


Fig. 5 Monthly average of power output

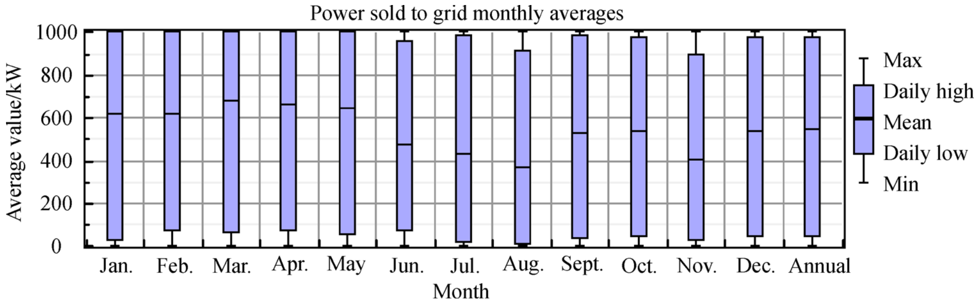


Fig. 6 Monthly average of power sold to grid

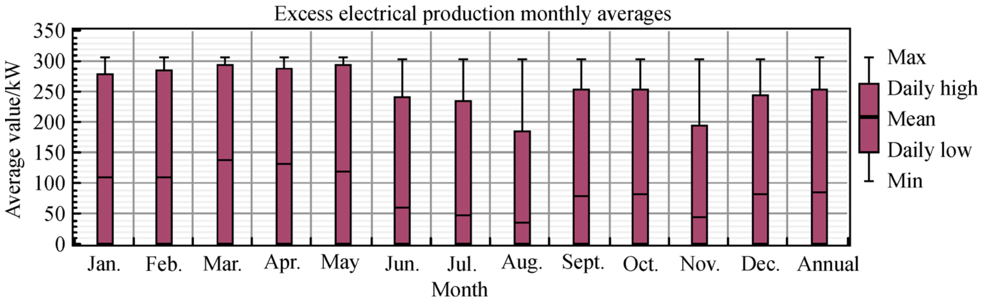


Fig. 7 Monthly average of excess electrical production

Table 5 Data of power grid for the proposed turbine

Month	Energy purchased /kWh	Energy sold /kWh	Net purchases /kWh	Peak demand /kW	Energy charge /$	Demand charge /$
Jan.	136	457507	−457371	6	−22848	0
Feb.	125	414910	−414785	6	−20721	0
Mar.	162	506028	−505866	8	−25269	0
Apr.	126	477640	−477514	6	−23857	0
May	146	476041	−475895	6	−23773	0
Jun.	237	338005	−337767	8	−16853	0
Jul.	237	315633	−315396	10	−15734	0
Aug.	331	274186	−273856	9	−13643	0
Sep.	222	380431	−380209	10	−18977	0
Oct.	175	399459	−399284	8	−19938	0
Nov.	248	292138	−291891	8	−14557	0
Dec.	183	400413	−400230	7	−19984	0
Annual	2328	4732391	−4730063	10	−236154	0

the HOMER software. It is important to remember that the wind power system is connected to the hydrogen system via the equalizer. Figure 8(a) shows the seasonal profile of the amount of hydrogen loaded in different months with the data downloaded from the official website of HOMER. Figure 8(b) shows the profile of hydrogen loaded in each hour of the day. Figure 8(c) shows the D-map of the amount of hydrogen loaded in each hour of the day and in different months.

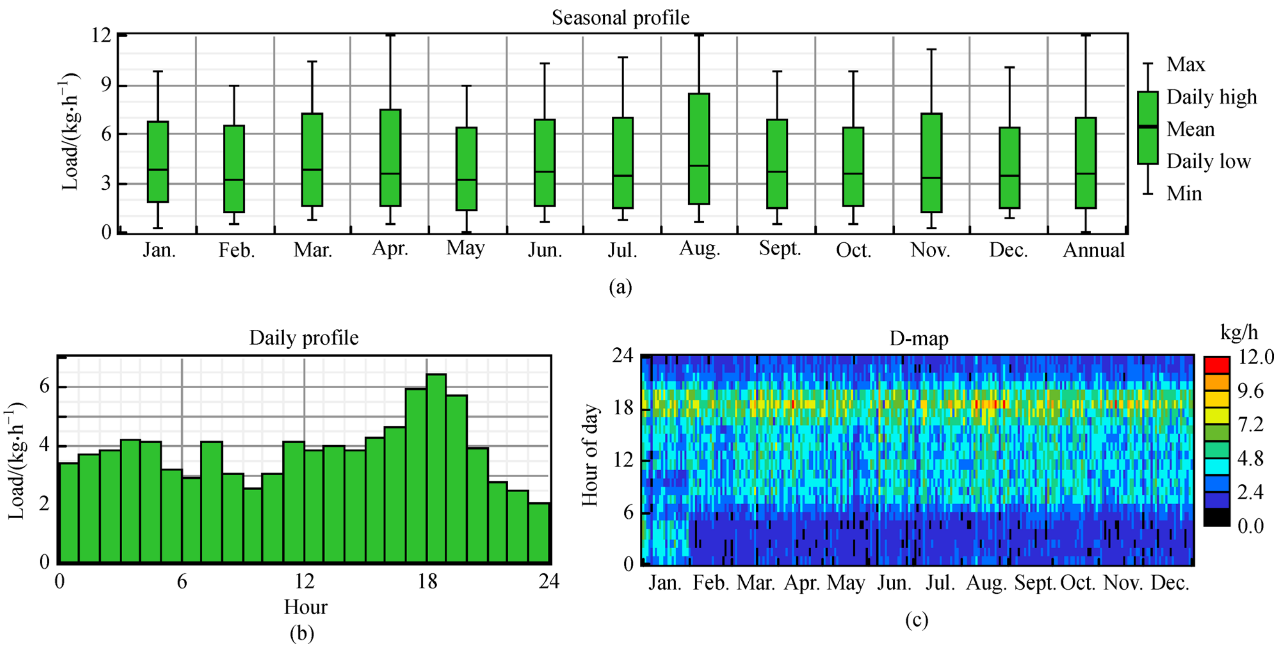
Figure 9 shows the hydrogen output of the reformer in different hours of the day and different months. According to Fig. 8, a rate of 2.4 to 5.2 kg of hydrogen per hour can be achieved in a majority of the hours in a day. Figure 10 shows the average monthly production of hydrogen for the pollution Firuzkuh similar to Fig. 9. The difference between Fig. 9 and Fig. 10 is that Fig. 9 is a D-map diagram for different hours of a day and different months but Fig. 10 is a quantize diagram and is related to the monthly average.

The average monthly production of hydrogen is shown in Fig. 11. According to Fig. 11, August and March with 92 and 85 kg of hydrogen per day have respectively the highest and lowest amounts of hydrogen production.

Therefore, the technical-economic feasibility of each proposed wind turbine was analyzed. The ranking was done by BCC and the appropriate turbine for construction of a wind power plant was selected. Then, the technical feasibility of hydrogen production was performed in the cycle of simulated power plant for the appropriate GE 1.5sl turbine with a management innovation. Finally, the results of the HOMER software were described for simulation of the wind-hydrogen fusion system.

5 Conclusions

Selecting the appropriate turbine for the construction of wind power plants is a key step in the construction of wind power plants or hybrid power plants which include wind energy. There have been several commonly used methods to select the appropriate wind turbine for the construction of wind power plants such as software simulations based on the wind speed of the area studied and the output of the wind turbine. But it seems that characteristics such as wind speed of the area studied, the amount of power generated by each proposed turbine, the revenues, the costs of wind



(a)

(b)

(c)

Fig. 8 Seasonal profile of amount of hydrogen loaded in different months

(a) Seasonal profile of hydrogen load; (b) daily profile of hydrogen load; (c) D-map of the amount of loaded hydrogen

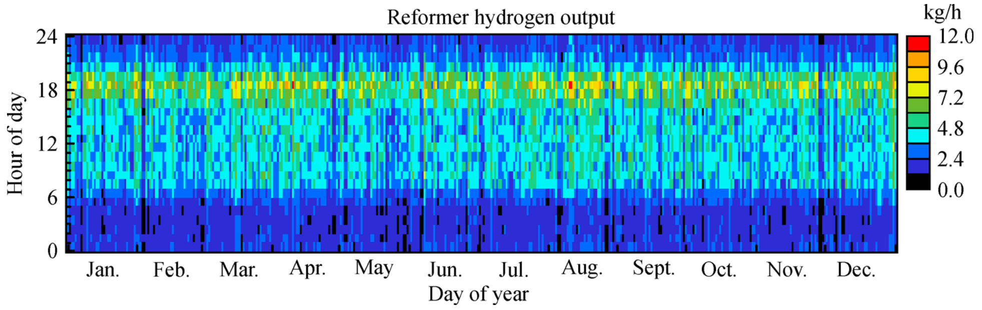


Fig. 9 Hydrogen output of the reformer

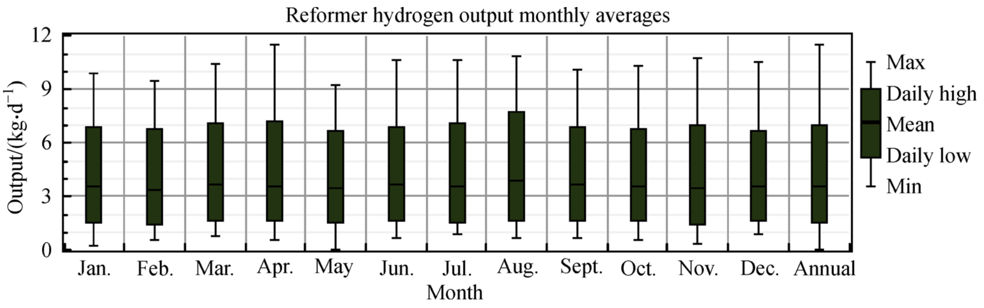


Fig. 10 Monthly average of reformer hydrogen output

power system, and the pollution caused by it must be initially simulated to select the appropriate turbine for the construction of the wind power plant or combined power plants including wind energy. Other influencing factors must also be considered in the process of selecting the appropriate turbine. Accordingly, the present study was conducted with the aim of selecting the appropriate turbine for the construction of a wind power plant in Firuzkuh, Tehran, using technical-economic feasibility in the HOMER software for several turbines proposed. Factors

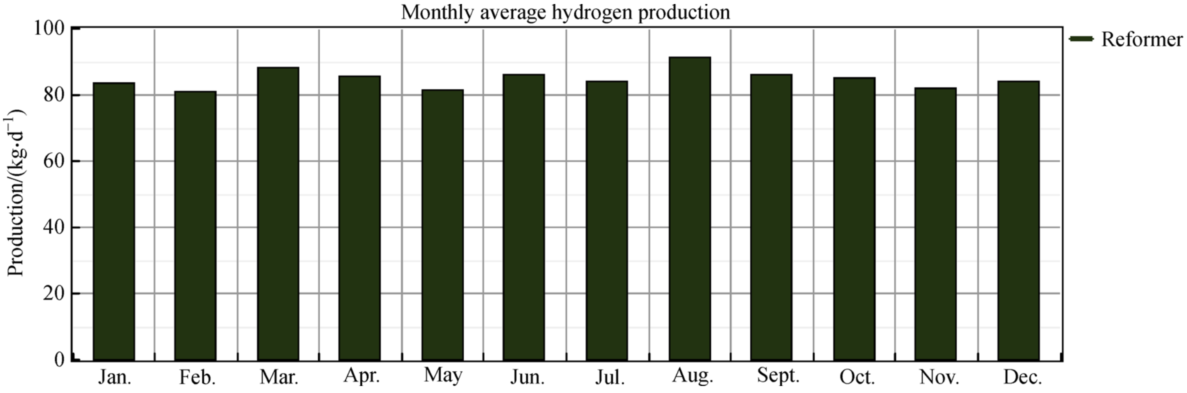


Fig. 11 Monthly average production of hydrogen

affecting the selection of the appropriate turbine for construction of a wind power plant were initially selected using the DEMATEL technique. These factors included the amount of electricity generated by each turbine, the revenues, the costs, the grid sales, and the total amount of electricity produced by each plant. Then, the technical-economic feasibility of each turbine proposed was analyzed using wind power system simulation in the HOMER software and the results of these processes were used as the input of the envelopment analysis model. On the other hand, among the various techniques of DEA, BCC was used for ranking because of being input oriented. The code of the BCC model was implemented in the Matlab software and the performance score of five factors proposed was obtained for each of the turbines proposed. After that the ranking was done and the GE 1.5sl turbine was selected as the appropriate turbine for the construction of the wind power plant in Firuzkuh with an annual electricity output of 5515325 kWh for each GE 1.5sl turbine and the annual revenues of $ 1103065. Finally, the hydrogen-wind fusion system was simulated using the HOMER software and the results showed that an average of 1014 kg of hydrogen was annually obtained. The results also indicated that the wind-hydrogen system was technically and economically approved.

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