Using wind turbines for hydrogen production: A case study

Ali Mostafaeipour
Industrial Engineering Department
Yazd University
Yazd, Iran
mostafaei@yazd.ac.ir

Omid Alavi
Department of Electrical Engineering
K.N. Toosi University of Technology
Tehran, Iran
omidal1370@gmail.com

Abstract

The potential of wind energy for hydrogen production is investigated in this paper for Fars province of Iran. Wind speeds at the elevations of 10 m, 30 m and 40 m recorded in ten minutes intervals for the period of one year were analyzed for cities of Abadeh, Juyom, Eqleed, and Marvdasht .Based on statistical analysis, city of Abadeh found to be the best for this purpose. The performances of four different large-scale wind turbines for producing wind power in Abadeh are evaluated. It is found that hydrogen from wind energy in Abadeh using a hydrogen producing unit would fuel approximately 266 cars per week if a REPower RE5M model wind turbine to be used.

Keywords
Wind energy; Hydrogen; Wind turbine; Weibull function; Fars province.

1. Introduction

Hydrogen production from renewable sources is considered as an appealing target for a gradual evolution to a clean economy and a more sustainable and smart energy mix [1, 2]. Hydrogen can be generated via utilization of renewable energy such as wind energy by electrolyzing the water without emission of carbon dioxide or other hazardous gases and dependency to fossil fuels [3, 4, and 5]. Hydrogen produced from different renewable energy sources like wind used as a fuel can be a good substitute to reduce greenhouse and other emissions, and reduces dependency from fossil fuels [6]. On this account, many investigations have been performed on wind-hydrogen systems in recent years.

Rodrıguez et al. [7] evaluated the potential of generating hydrogen using wind energy in the province of Cordoba, Argentina. They investigated the possibility of using hydrogen for vehicular transportation in the examined area. The achieved results indicated that the potential of wind energy in the province is high enough for providing ten times of the required hydrogen to supply the energy of whole vehicular transportation. Aiche-Hamane et al. [8] performed a study to determine the viability of hydrogen generation from wind energy in Ghardaia, Algeria. They estimated the hydrogen rate which can be generated via a 5 kW electrolyser fed using the electricity supplied by a wind turbine with 10 kW rated power. Their results showed that 3200 m^3 hydrogen can be produced by the wind turbine with 30 m height and 4200 m^3 by the wind turbine with 60 m height.

Zhang and Wan [9] investigated a wind-hydrogen energy storage system model for massive wind energy curtailment. They investigated a model of integrating curtailed wind energy with hydrogen energy storage using 10 minutes interval wind speed data from the wind farm located in central north of Inner Mongolia with 66 Goldwind's GW77/1500 PMDD wind turbines. They performed economic evaluation using payback period methodology. They found that hydrogen energy storage technology using wind energy would economically be viable. Sanchez et al. [10] illustrated economic evaluation of wind park based on a hydrogen compensation system consists of combining wind energy production with a biomass gasification system and a hydrogen generation system based on these two sources. They concluded feasibility of implementing this system. Patrıcio et al. [11] investigated wind hydrogen energy system and its gradual replacement of natural gas in the State of Ceara in Brazil. They proposed the solar hydrogen energy system created by Veziroglu and Basar in the 70's. They proposed that the system would start in the year 2015 and predicted that it would have revenue US$ 730 million in the slow scenario. Sarrias-Mena et al. [12] proposed a model for hydrogen production from wind energy. They investigated the coupled operation of electrolyser and wind turbine with four different models which were evaluated and compared under different conditions. The simulation results revealed a satisfactory operation between the wind turbine and all the models.

2. Status of wind energy use in Iran

Recently, tendency of using wind energy to produce electricity in Iran has been significantly increased and government has placed appropriate reimbursements for renewable production of electricity. Among the Middle Eastern countries, Iran is the major country that has generated wind power. The potential of electricity generation by wind energy in Iran is about 10,000 (MW). Iranian Renewable Organization (SUNA) has done a considerable research in this regard; Iranian wind atlas was prepared by this organization [13]. The main wind power stations in Manjil and in Binalood have capacities of 70MW and 28MW to generate electricity, respectively [14]. Persia (Iran) was one of the first countries in the world that used renewable energies in ancient time [14].

Many researchers have been studied about implementing renewable energies in the literature [15-30]. Mohammadi and Mostafaeipour[15] investigated estimation of wind energy potential for city of Zarrineh in Iran. They also tried to find the best method of calculating wind power among the standard deviation method and the power density method. It was found that the city of Zarrineh did not have potential for large wind turbines. Mostafaei and Abessi [16] performed a thorough study on productivity and development of wind turbines in Iran. Shamshirband et al.[17] used Extreme Learning Machine method for city of Aligoodarz in west of Iran to predict Weibull k and c factors. They used long-term measured wind speed data for 5 years. It was concluded that ELM was suitable method for prediction of two factors.

Mostafaeipour et al. [18] performed a research for city of Yazd in Iran to find out whether wind energy could be economically feasible for cooling and ventilation of medicine storage warehouses. The research showed that traditional wind catchers could be useful in order to lower elctricity sodt for this purpose. Mostafaeipour [16] has analyzed the wind energy potential for installing the wind turbine among 11 sites in Yazd Province by using wind data measured during 13 years. Harat city has been suggested by him as the best location for setting up the wind turbines. Furthermore, because of high potential of Manjil city, possibility of increasing wind power generation and the number of turbines has been suggested by Mostafaeipour and Abarghooei [14]. In this study, the wind energy potential locations in province of Fars are assessed for four cities: Abadeh, Juyom, Eqleed, and Marvdasht. No previous study on wind potentials for Fars province is reported in literature. This is part of international efforts for characterizing wind map of Iran for utilizing wind energy and other renewable energies in this region.

3. Geographic characteristics of Fars Province

Fars province is located in the southern part of Iran with area of 133,000 km^2 which constitutes almost 1.8% of Iran. It is located in $52^{\circ}35'$ longitude and $29^{\circ}39'$ latitude. Figure 1 shows map of Iran including four investigated cities in Fars Province for generating electricity by wind turbines [31, 32].

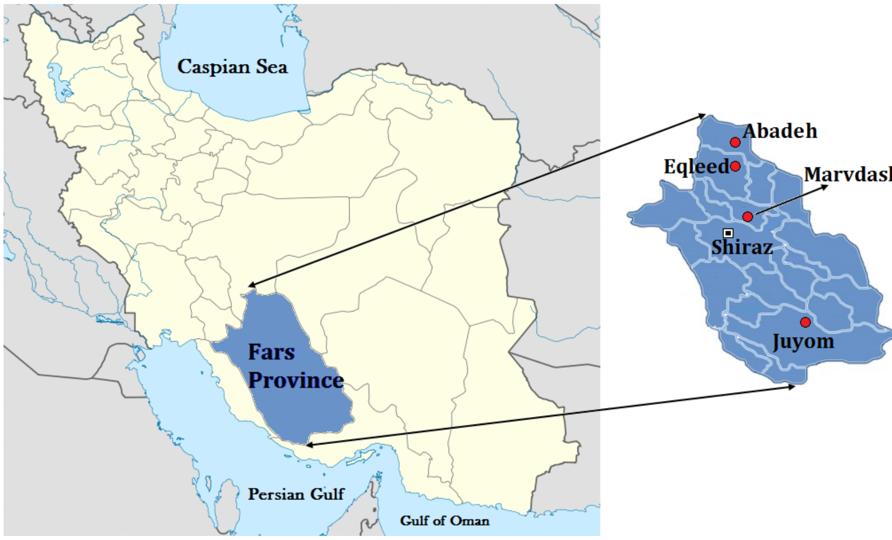

Fig. 1: Fars Province in Iran.

Table 1 illustrates the geographical latitude and longitude of the of four cities in the province.

Table 1: Geological latitude and longitude of the examined sites in Fars province.

Site	Latitude	Longitude
Abadeh	31°10′	52°37′
Juyom	28°19′	54°08′
Eqleed	30°55′	52°39′
Marvdasht	29°50′	52°40′

4. Wind speed characteristics

4.1. Wind speed distribution

It is a matter of common observation that the wind is not steady and in order to calculate the mean power delivered by a wind turbine from its power curve, it is necessary to know the probability density distribution of the wind speed. This is simply the distribution of the proportion of time spent by the wind within narrow bands of wind speed. The basic measure of the unsteadiness of the wind is the standard deviation (or root mean square) of the speed variations and this almost certainly representative of the unsteadiness of the wind everywhere in order to calculate the mean power from a wind turbine over a range of mean wind speeds. A generalized expression is needed for the probability density distribution. An expression which gives a relatively good fit to wind data is known as the Weibull distribution [33, 34].

Therefore, the two-parameter Weibull distribution is used in this study for analyzing the wind data in Fars province. The probability distribution function of the two-parameter Weibull distribution is given by [35, 36]:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right] \quad (1)$$

where U is wind speed (m/s), k is shape factor (dimensionless) and c is scale factor (m/s). k and c can be obtained, respectively by [36, 37]:

$$k = \left(\frac{\sigma_U}{\overline{U}}\right)^{-1.086} \quad (2)$$

$$\frac{c}{\overline{U}} = \frac{k^{2.6674}}{0.184 + 0.816k^{2.73855}} \quad (3)$$

where σ_U and $\overline{U}$ are the standard deviation and mean wind speed, respectively.

4.2. Evaluation of Weibull distribution

The goodness-of-fit of a statistical model describes how well it fits a set of observations. Measures of goodness-of-fit typically summarize the discrepancy between observed values and the values expected under the model in question. Unfortunately, there are no formal standards for how to evaluate the quantitative goodness-of-fit of models to data, either visually or numerically. As a result, there is considerable variability in methods used, with frequent selection of choices that misinform the reader. In the present paper, MATLAB software is used to fit wind data in which the suitability of the distributions is judged from the root mean square error (RMSE). The RMSE parameter gives the deviation between the predicted, y_i, and the experimental values, x_i; it should be as close to zero as possible, and it is expressed as:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{(y_i - x_i)^2}{N}} \tag{4}$$

RMSE values close to zero is observed for all data studied in this research work.

4.3. Wind power and energy density

A quantitative measure of the wind energy available at any location is called the wind power density [35, 38]. It is a calculation of the mean annual power available per square meter of swept area of a turbine, and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Therefore, one of the significant parameters which must be computed to indicate how much energy is available at the site is wind power distribution (P/A). This amount is proportional to air density (ρ) and the cubic of average speed $\overline{U}^3$ [39]

$$\frac{\overline{P}}{A} = \frac{1}{2}\rho K_e \overline{U}^3 \tag{5}$$

Also, wind energy density is computed as:

$$\frac{\overline{E}}{A} = \left(\frac{\overline{P}}{A}\right)(N\Delta t) \tag{6}$$

where N is the number of measurement period, and Δt is the time interval. The energy pattern factor, K_e, is defined as the total amount of wind power available divided by the power calculated from cubic average wind speed:

$$K_e = \overline{U^3} \Big/ (\overline{U})^3 \tag{7}$$

In Eq. 7, $\overline{U^3}$ is the cubic average wind speed. The following power density criterion is to evaluate suitability of the sites [39]:

$$\begin{aligned} \frac{\overline{P}}{A} &< 100\,\frac{W}{m^2} \quad poor \\ \frac{\overline{P}}{A} &\approx 400\,\frac{W}{m^2} \quad good \\ \frac{\overline{P}}{A} &> 700\,\frac{W}{m^2} \quad great \end{aligned} \tag{8}$$

As it is indicated in Eq. 6, if the power density per area is smaller than 100 (W/m^2), it cannot be suitable to setting up wind turbines and if it is equal to 400 (W/m^2), the condition is appropriate and finally if power density per area is more than 700 (W/m^2), the great performance may be expected from wind turbines [35].

5. Wind speed characteristics

5.1. Nominal and most probable wind speeds

The nominal wind speed is another substantial character and can be defined as a speed that produces maximum energy along the year. With using nominal wind speed, maximum energy can be captured throughout of a year [35].

$$U_{me} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{9}$$

And the most probable wind speed for the area is given by [35]:

$$U_{mp} = c(1 - \frac{1}{k})^{\frac{1}{k}} \quad (10)$$

This is a good measure in power capture of a wind turbine.

5.2. Calculation of energy production by wind turbines

To estimate the amount of energy that can be generated from wind turbines in any location, the performances of wind turbines must be analyzed. Capacity factor (C_F) is a significant parameter of the productivity of wind turbine. C_F is the ratio of the output power (P_{out}) by the wind turbine over period of time to the rated power (P_r) which can be computed as [40, 41]:

$$C_F = \frac{P_{out}}{P_r} = \frac{e^{-\left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_o}{k}\right)^k} \quad (11)$$

where v_i, v_r and v_o are cut-in speed, rated speed and cut-out speed respectively.
Then the energy output of wind turbine for any time period (*T*) is calculated by:

$$E_{out} = C_F P_r T \quad (12)$$

6. Results and discussion

Table 2 presents the attained mean wind speeds at three heights of 10 m, 30 m and 40 m for the four selected sites in the Fars province of Iran. It is found that among the examined sites, the highest mean wind speeds belong to city of Abadeh.

Table 2:Annual mean wind speed (m/s) in 2006-2007 at three heights for the four selected sites in the province.

Site	40m	30m	10m
Abadeh	5.38	5.17	4.52
Juyom	2.58	2.42	1.85
Eqleed	4.39	4.20	3.84
Marvdasht	3.41	3.28	2.88

Different wind characteristic such as Weibull parameters *k* and *c*, energy pattern factor, power density, energy density and turbulence intensity at 40 m height for four examined sites in the Fars province are given in the Table 3.

Table 3: Wind characteristics

Sites/parameters	*k*	*c*	*Ke*	*P/A*	*E/A*
Abadeh	1.732	4.795	2.36	225.2	1972.7
Juyom	1.246	2.412	3.83	40.7	356.6
Eqleed	1.105	4.239	1.69	87.9	770.3
Marvdasht	1.657	3.051	2.46	60.0	525.7

According to Table 3, it is observed that city of Abadeh has the highest potential for wind energy harnessing compared to other selected cities. Thus, Abadeh site is considered and analyzed in detail to determine the capacity of this site. Wind characteristics of Abadeh at three heights are shown in Table 4.

Table 4: Characteristics of wind for Abadeh

Parameters/heights	40	30	10
k	1.732	1.734	1.734

c	4.795	4.606	4.031
Ke	2.36	2.36	2.37
P/A	225.2	200.4	134.6
E/A	1972.7	1754.9	1179.1
U_{me}	7.47	7.16	6.27
U_{mp}	2.24	2.24	2.20

Annual wind power density at 10 m, 30 m and 40 m heights are illustrated in the Fig. 2. According to the wind power classification criterion presented by Eq. 5, the wind potential of the site is fairly good and can be considered acceptable to install wind turbines. The wind power densities are between 169 and 173 W/m^2 at 10 m, between 200 and 205 W/m^2 at 30 m and also between 220 and 225 W/m^2 at 40 m height.

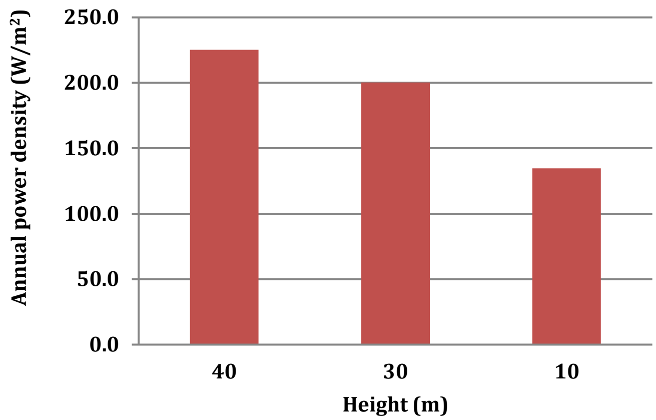

Fig. 2. Annual power density at 40 m, 30 m and 10 m for the city of Abadeh

7. Hydrogen production in Abadeh

To determine the amount of hydrogen which can be generated via wind energy in city of Abadeh, which has the best wind energy potential among examined cities in the Fars province, the performances of some selected wind turbines in terms of electricity generation are assessed first. Table 5 offers technical data of the selected wind turbines with hub height of 40 m. Four different commercial wind turbine models were selected for analyzing wind potential to produce hydrogen. These four wind turbines were selected from an inventory of available wind turbines in the market with the hub height of 40 m.

Table 5: Technical data of selected wind turbines with hub height of 40 m [42,43].

Wind turbine model	Rated Power (KW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out Speed (m/s)	Annual Average Power (kW)	Eout (GWh)
Vestas V90	3000	4	17	26	425.27	3.55
Vestas V122	3000	3	13	25	629.66	5.13
REPower RE5M	5000	4	15	31	811.47	6.72
REPower RE6M	6000	4	15	31	829.17	6.93

Total annual energy output of the nominated wind turbines for city of Abadeh is illustrated in Table 5. It shows that REPower RE6M model turbine is capable of generating 6.93 GWh of electricity.

The electrolyzer is able to produce 1 kg/day of hydrogen with a 3 kW power unit or 26 MWh annually is required. But for producing 1000 kg/day of hydrogen, a bigger unit with 2.3 MW of power or 20 GWh annually is required [44].
Table 6 illustrates amount of hydrogen which could be produced in city of Abadeh considering four different turbine models. The 1 kg/day hydrogen production unit would fuel 1 car per week [44]. Hydrogen from wind energy in Abadeh using a hydrogen producing unit would fuel approximately 266 cars per week if a REPower RE6M model wind turbine to be used.
This boundary analysis indicates that wind energy is available to produce hydrogen in the region.

Table 6: Amount of hydrogen production considering wind turbine models for city of Abadeh.

Wind turbine model	Produced hydrogen (car/week)
Vestas V90	136.53
Vestas V122	197.30
REPower RE5M	258.46
REPower RE6M	266.54

Total annual energy output of 6.93 GWh for city of Abadeh, using REPower RE6M model wind turbine, is capable for producing hydrogen fuel to supply approximately 266 cars per week.
Hydrogen is a light element which has atomic weight of 1.0, but liquid hydrogen has density of 0.04 grams/cm^3. By comparing energy contain of gasoline with hydrogen, we could see that 9.5 kg of hydrogen is almost equivalent to 25 kg of gasoline. A 14 kg tank is required to store 25 kg of gasoline, but the storage of 25 kg of hydrogen needs a tank of 145 kg mass. Reason for this difference is that volume hydrogen fuel is 4 times greater than gasoline fuel. Also, efficiency of hydrogen is 1.33 bigger than gasoline for automobiles [45].
There are 200 cars per 1000 people in Iran. For the population of 98,188 in Abadeh [46], therefore, 98.188×200=19638 cars are running in the city. Almost 97 kg hydrogen is required per car annually [46]. Therefore, 1,904,886 kg hydrogen is needed annually for the car fleet in Abadeh.
REPower RE6M model wind turbine generating hydrogen for 266 cars per week or 4.84 cars per year, or nearly one wind turbine for five cars. Hence, we need 19638/5=3927.6 wind turbines or nearly 4000 wind turbine to fuel all the cars. But, different larger kinds of wind turbines with bigger rotor diameters could be used to lower the numbers of wind turbines in the area to produce same amount of hydrogen for all cars in the Abadeh.

8. Conclusions

In this study, the potential of wind energy in the Fars province of Iran is investigated for production of hydrogen as car fuels. For this purpose, wind energy potential of four cities of Abadeh, Juyom, Eqleed, and Marvdasht in the Fars province of Iran are evaluated using ten minutely recorded wind speeds at 10 m, 30 m and 40 m heights and wind direction at 30 m and 37.5 m heights for the period of one year .It is found that the city of Abadeh has better potential with wind power of (169–173) W/m^2 at 10 m, (200–205) W/m^2 at 30 m, and (220–225) W/m^2 at 40 m heights for installing wind turbines. The annual electrical power production in the city of Abadeh from four large wind turbines of Vestas V90, Vestas V122, REPower RE5M, and REPower RE6M are determined. It is found that REPower RE6M model wind turbine with 6.93 GWh annual electrical productions is capable of fueling 266 cars per week.

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Biography

Ali Mostafaeipour is an assistant professor of Industrial Engineering at Yazd University, Iran. He has been teaching at Yazd University since 1989. He studied at Winona State University (University of Minnesota) in state of Minnesota, USA; University of Wisconsin at Platteville, Wisconsin, USA; Alabama A&M, Alabama, USA; and Iran University of Science and Technology, Tehran, Iran. He has served as a committee member, guest speaker, and co-chairman of 117 international conferences. He has been reviewer of 17 international journals mainly Elsevier. He has presented 73 mostly International conferences throughout the world. He has undertaken and managed 18 research projects, and holds 3 patents. He has been editorial board of several professional journals. Finally, he has published 51 journal articles mostly at Elsevier (ISI), and he authored 4 books. He holds an award for excellence from Yazd University as the year 2013 distinguished researcher, also distinguished author of "Wind Energy" book (INTech publisher, 2012, Croatia) with more than 5000 downloads in six months. His research interest lies in renewable energies, wind energy, value engineering, economic evaluation, and feasibility study of projects.

Omid Alavi was born in Zahedan, Iran, in 1991. He received the B.S. degree in electrical engineering from Ferdowsi University of Mashhad, Iran, in 2014. He is currently with the department of electrical engineering, K.N. Toosi University of Technology, Tehran, Iran. His research interests include renewable energies, wind turbine design, power electronic devices, reliability, and resource assessments. He published several international papers in highly ranked journals. He is also the reviewer of some journals, such as "Electric Power Systems Research", "Energy" and "Energy, Sustainability and Society".