Evaluation of hydrogen production from wind turbines: A case study

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Abstract

In recent years more attention has been paid to renewable and clean sources of energy like wind. Due to the uncertainties related to wind turbines, issues of energy storage are significant. One of the most appropriate methods of energy storage is the production of hydrogen. The main aim of this paper is to investigate the capability of wind energy for producing hydrogen in Pincher Creek in Alberta, Canada. This paper analyzes four different wind turbines with a capacity of 300 to 900 kW in the selected location. In this study, two approaches were used; the actual average wind turbine power and the Weibull. It was found that EWT Directwind 500/54 provides the best capacity factor among all examined turbines with the highest value of 22.05%. Additionally, the highest energy production was from the same wind turbine with an annual production of 966 MWh. A wind-hydro system consisting of a power controller, a high efficiency rectifier, and an alkaline electrolyzer was considered. The proposed conversion system resulted in a linear relationship between generated wind turbine energy and the amount of hydrogen produced. Therefore, the highest amount of yearly hydrogen production (15.62 ton-H2) is related to the EWT Directwind wind turbine.

Keywords
Wind energy; Weibull distribution; Resource assessment; Hydrogen production; Canada.

1. Introduction

Wind and solar power are the most important sources of renewable energies and both are abundant in many countries. Wind is important because of its many advantages, such as low cost, clean, abundant, inexhaustible, and environmentally friendly. Wind turbine technology has increased over the past few decades in many countries, and many governments have decided to enhance the knowledge about wind turbine technologies for electricity generation [1]. Among the methods of electricity generation from renewable energies, wind turbines are believed to be the best and most cost-effective option. Of course, in terms of the problems associated with the instability caused by wind turbines to the power grid, the importance of energy storage systems, particularly hydrogen fuel, is more significant now [2].

Mostafaei and Abesi [3] investigated a thorough study to analyze productivity of wind turbines and their developments in Iran. They investigated offshore wind turbines in Iran, but there have not yet been any installed offshore turbines in Iran. Shamshirband et al. [4] evaluated proficiency of using Extreme Learning Machine (ELM) for estimating the monthly wind speed distribution. They concluded that this method was conclusively promising. Another application of wind energy is using wind catchers that are able to harness wind energy for cooling and ventilating of the houses

[5]. There have been other literatures which investigated the predictions of different parameters for renewables energies [6-8].
Hydrogen is widely known as an ideal energy carrier in the foreseeable future, and it can be produced from water without CO_2 emissions by utilizing various sources of energy, such as wind, solar, and others [9,10]. By converting hydrogen into a usable form of energy, we will have an environmentally friendly, permanent, and clean source.
Different studies have been conducted on the importance of hydrogen production from different renewable energy sources, particularly wind energy. In [11], the first mathematical model was introduced for the long-term calculations of technical and environmental indicators based on the solar-hydrogen system in the 1970s. This model became popular after publishing this study so that the model was used on the various case studies, for instance, Brazil [12], Saudi Arabia [13], Egypt [14], Spain [15], and Pakistan [16].
Mostafaeipour et al. [17] evaluated the potential of wind energy in order to produce hydrogen at four stations of Fars province, Iran. It was found that the station at Abadeh (with a yearly average power density of 220 W/m2) has the greater wind energy potential in comparison with other selected stations. The calculations showed that a 900 kW wind turbine can produce required hydrogen for 22 cars per week. There are many research papers related to wind energy which are in literature[18-26].
The main purpose of this research is to analyze hydrogen production from wind energy for a selected location of Pincher Creek situated in Alberta province in Canada. In order to provide a comprehensive evaluation, four different wind turbines of Vestas V47, AWE 52-900, EWT Directwind 500/54, and Nordtank-300 with different rated powers and characteristics were investigated. The main contribution of this study is that it was the first time that hydrogen production from wind energy was investigated in the region, also two different methods of actual values and Weibull were employed for the examination.
The rest of this paper is organized as follows: In Section 2, the case study and wind data are presented. Section 3 describes the methodology and the proposed wind-hydro system. Section 4, presents the results and discussions related to the analysis of wind energy and hydrogen production. In Section 5, conclusions are drawn.

2. Case studies and wind speed data

Canada is among the major countries that have successfully considered the wind power development in recent years. With total installed wind turbines capacity of around 9700MW by the end of 2014, Canada has established itself as the 7th leading wind market in the world. With the rapid growth in terms of installation, wind power market has reached to the level that supplies around 4% of Canada's electricity demand [18]. Alberta as a western province of Canada is recognized as one of the most important regions of Canada regarding the wind energy utilization. Alberta with the total area of 661,848 km2 is the sixth largest province of Canada. It is located between the geographical locations of 49° to 60° N and also 110° to 120° W. By the end of 2014; Alberta with an installed wind energy capacity of 1471MW ranked third in Canada [27].
Alberta province is well positioned to take advantage of remarkable wind energy potential throughout the year. For this study, a well-known location namely Pincher Creek was selected as case study.

Figure 1. Location of the selected location on the map of Canada

Fig. 1 illustrates geographical location of Alberta and the selected site on the map of Canada. Table 1 lists latitude, longitude and descriptive statistics, such as maximum, mean, standard deviation, skewness, and kurtosis to describe wind speed characteristics for the selected location.

Table 1. Geographical location and descriptive statistics of the studied station

Mean	4.43 (m/s)
Max	23.13 (m/s)
Standard deviation	2.85
Skewness	1.04
Kurtosis	4.59
Longitude	113°59'50.000" W
Latitude	49°31'14.000" N
Elevation	1,189.60 m

Wind speed data at the height of 40 m for the site under consideration are measured Environment Canada [28]. The wind speeds data were recorded by a cup anemometer in 1-hour intervals.

3. Methodology

Determining an accurate scheme of wind characteristics plays a prominent role in finding a suitable location to install wind farms. Wind speed distributions are a practical way to model wind behavior using a limited number of parameters. By knowing the wind speed distribution in a location, we can determine the economic factors affecting the wind turbine's performance. Different distribution functions have been used to be fitted on the actual wind speed data, and these include Weibull, gamma, Rayleigh and lognormal [29].

3.1 Weibull distribution function

Rayleigh and Weibull are the most widely used methods for analyzing the wind power. Since the Rayleigh function is a special case of the Weibull, only the Weibull function has been used in this study. Weibull distribution function has enormous advantages in comparison to others. These include great flexibility, a small number of parameters, a simple parameter estimator, and a very close fit to the data [30]. The severe limitation of the Weibull distribution is improper results for near-zero wind speed data. However, due to the low wind speeds below 3.5 m/s, this does not matter for wind resource assessments. Since wind turbines cannot be affected by these wind speeds, the influence of this problem is negligible [31].

To determine the Weibull distribution, it is necessary to know the shape parameter (dimensionless) and the scale parameter (m/s). Different methods are used to estimate these parameters, such as maximum likelihood estimator (MLE), method of moments (MOM), modified maximum likelihood estimator (MMLE) and others. In [32], the authors found that the MLE method produces more appropriate results than other methods.

The probability density function (PDF) of the two-parameter Weibull distribution is as follows [33]:

$$f(v,k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp[-\left(\frac{v}{c}\right)^{k}] \quad (1)$$

where *v*, *k* and *c* are wind speed, shape and scale factor, respectively. The shape parameter (also known as the Weibull slope) exhibits the shape of distribution peak [34]. The effect of changing the scale parameter is similar to the abscissa scale of the wind speed distribution [35]. An evaluation of previous works demonstrates that the shape parameter for the windiest regions is in the range of 1.2 to 2.75.

The cumulative distribution function (CDF) can be obtained by [36]:

$$F(v) = 1 - exp\left(-\left(\frac{v}{c}\right)^{k}\right) \quad (2)$$

In this paper, the MLE method is used to determine the Weibull parameters. The MLE is a mathematical expression identified as a likelihood function of the wind speed data in the format of time series. In this method, multiple numerical iterations are essential to determine two parameters of the Weibull function. The *k* and *c* parameters are calculated by solving two following equations [33]:

$$k = \left[\frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} - \frac{\sum_{i=1}^{n} \ln(v_i)}{n}\right]^{-1} \quad (3)$$

$$c = \left[\frac{\sum_{i=1}^{n} v_i^k}{n}\right]^{\frac{1}{k}} \quad (4)$$

where v_i is the wind speed in time step i, and n is the number of nonzero recorded wind speed data.

3.2 Wind turbine energy production

Energy production from the wind turbine installed in a location with a given wind probability distribution and a recognized wind turbine power curve, is as follows [37]:

$$P_{WT} = \int_0^{\infty} f(v)\, P_C(v)\, dv \quad (5)$$

where $f(v)$ is the Weibull probability distribution function, and P_C is the power curve estimated using curve fitting in form of a sextic polynomial equation.
The above equation will present the actual average wind turbine power, if we use the empirical probability distribution values instead of the Weibull. Also, the annual energy production from wind turbines can be calculated by:

$$E_{WT} = P_{WT} \times 8760h \quad (6)$$

An important factor that shows the ratio of the actual wind turbine power generated to the wind turbine rated power, is the capacity factor. The performance of a wind turbine installed at a location is related to its capacity factor, and the most proper installed turbine will have the highest value of this parameter. In the present study, four different wind turbines were considered for the analysis. The wind turbine characteristics manufactured by four companies are listed in Table 2. The rotors of all the turbines are equipped with three blades. Hub height and frequent use in different wind farms have been important reasons for selecting these turbines. The pitch control system is applied to all chosen turbines except Nordtank NTK-300, which has a stall control [38].

Table 2. Characteristics of the selected wind turbines [38]

Model	Power (kW)	Hub height (m)	Rotor diameter (m)	Swept area (m^2)	cut-in speed (m/s)	rated speed (m/s)	furling speed (m/s)
Vestas V47	660	40	47	1,735	4	15	25
AWE 52-900	900	40	50	2,124	2	15	25
EWT Directwind 500/54	500	40	54	2,291	3	13	25
Nordtank-300	300	40	28	616	4	13	25

3.3 Hydrogen production from wind energy

The proposed system for converting wind energy to hydrogen is shown in Fig. 2. This system consists of a wind farm, power controller, a high efficiency AC-DC converter (also known as rectifier), and an alkaline electrolyzer which is supplied by a regulated DC voltage. In the first step of the energy conversion process, the produced electricity by wind turbines supplies the required electricity for water electrolysis system. By applying electricity through two electrodes of the used electrolyzer, hydrogen gas will produced via the alkaline electrolysis.

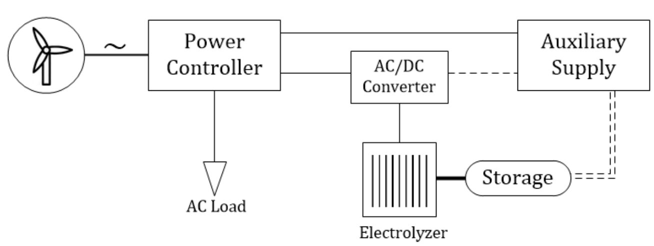

Figure 2. The proposed wind-hydrogen energy conversion system

To determine the amount of hydrogen produced by the considered system, definition of two parameters is essential: the efficiency of the used rectifier, and energy consumption of the electrolyzer. The efficiency of a rectifier depends on the various factors such as its topology and used components, and its value varies in the range of 80% to 95% [39]. In addition, the typical value of energy consumption of an electrolyzer is approximately 5-6 kWh/Nm3 [40].
The amount of hydrogen produced by a wind farm has a direct relationship with the annual wind turbine energy production. Equation (7) expresses the amount of hydrogen (H_{WT}) in normal cubic meter [40].

$$H_{WT} = \frac{E_{WT}\,\eta_{conv}}{ec_{el}} \tag{7}$$

where η_{conv} is the converter efficiency, ec_{el} is the energy consumption of the electrolyzer.

4. Results and Discussion

In the present study, we evaluate wind speed data for the station at Pincher Creek in Canada. The wind speed data are analyzed and processed using Matlab, and the Weibull parameters are obtained. The main outcomes from the calculations can be summarized as follows:

4.1 Monthly mean wind speeds

In the first phase of study, the monthly mean wind speed can be calculated at the height of 40 m for the considered station, using averaging over data related to each month.

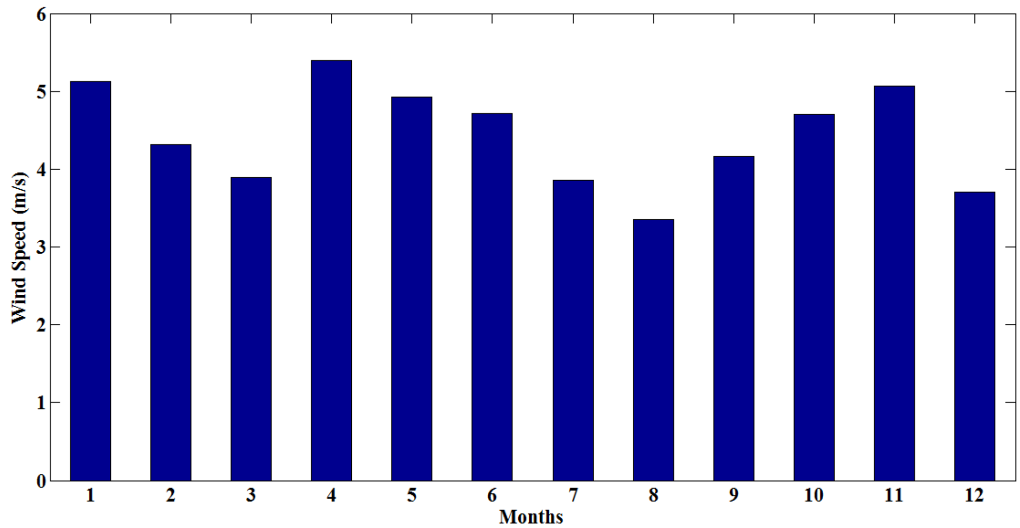

Figure 3. Monthly mean wind speed for the selected station

It is evident from Fig. 3 that April has the highest value of mean wind speed. Also, August exhibits the lowest mean speed with a value of 3.36 m/s. As seen, the average wind speed for the first six months of the year with a value of 4.73 m/s is higher than the second six months (4.14 m/s).

4.2 Weibull distribution

Equations (1) and (2) are used to carry out the Weibull probability and cumulative functions, respectively. Fig. 4 illustrates the probability density functions for the selected station at the height of 40 m. One weakness of this function is that it cannot precisely represent the probabilities of empirical data close to zero [41]. However, the Weibull distribution provided a good fit to the actual data in this study.

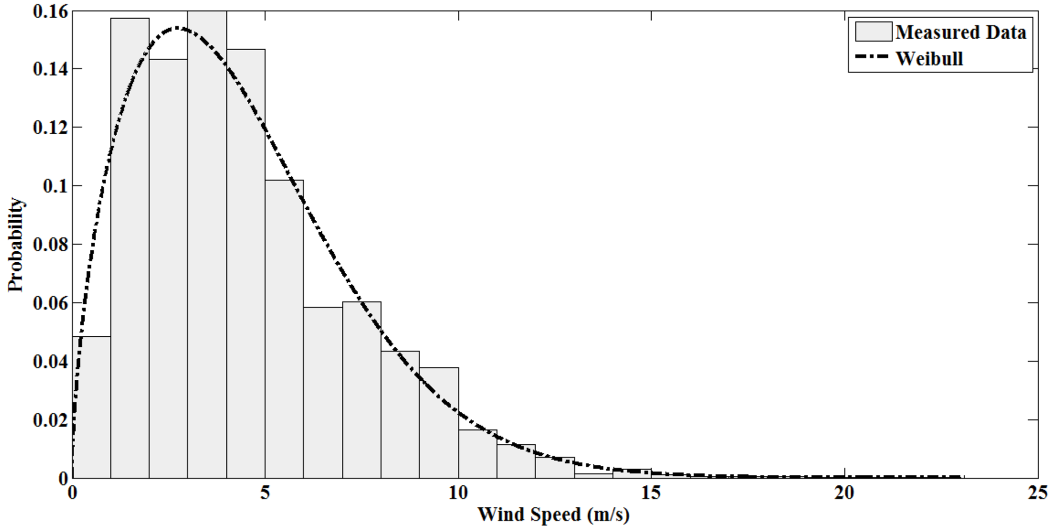

Figure 4. PDF of wind speeds

Bar chart shows the measure data in the scheme of histogram. The Weibull distribution exhibits that the wind speed of 2.7 m/s has the highest wind frequency at the height of 40 m with frequency being equal to 15.7% for the examined station.

Another useful statistical parameter is the cumulative distribution function, *F(v)*, which represents the area under the PDF from zero to *v*. For this reason, the highest value of wind speed reveals a probability of 1 for the CDF. Fig. 5 shows the cumulative distribution functions at 40 m for the studied station. The probability of wind speed greater than 5 m/s that mentioned before can be found by subtracting the value of CDF at the speed of 5 m/s from 1. A feature of this graph, which highlights the importance of its using in wind resource assessments, is that the probabilities of wind speed greater than the cut-out speed and wind speed lower than cut-in speed are conveniently visible.

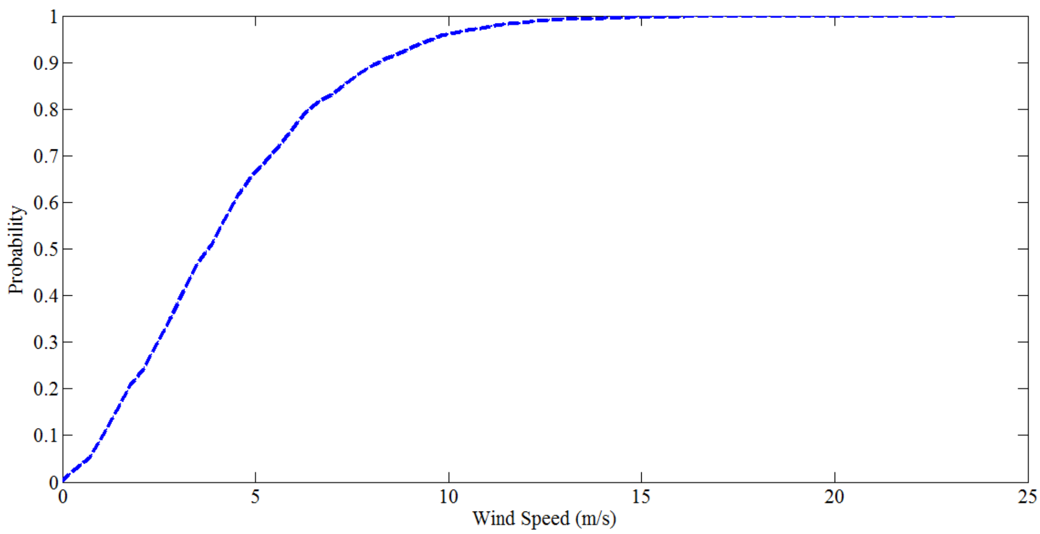

Figure 5. CDF of wind speeds for the nominated station

4.3 Wind turbine energy production

Four different wind turbines with capacities of 300 to 900 kW have been selected in this analysis. The calculations related to these wind turbines were conducted according to the height of the turbines under consideration, and the obtained capacity factors and annual energy production are given in Table 3. As mentioned before, two approaches – the actual average wind turbine power and the Weibull – were utilized to determine these factors. However, the outcomes of the two approaches are very close.

Table 3. Yearly average of wind power and energy for the nominated station

	Actual		Weibull	
Model	Capacity factor	Annual energy production (MWh)	Capacity factor	Annual energy production (MWh)
Vestas V47	0.1269	733.859	0.1258	727.198
AWE 52-900	0.1210	954.066	0.1194	941.487
EWT Directwind 500/54	0.2205	965.742	0.2168	949.499
Nordtank-300	0.1224	321.678	0.1197	314.495

Table 3 shows that EWT Directwind turbine has the best performance in terms of efficiency; however, it is able to produce about 1 GWh electricity in a year and this value is remarkable. Although the AWE 52-900 wind turbine has the highest rated power, it exhibits an improper capacity factor and also annual energy production.

4.4 Analysis of hydrogen production

In the present study, a rectifier with the efficiency of 90% and an electrolyzer with the energy consumption of 5 kWh/Nm3 were investigated. 1 kg of hydrogen is equal to 11.13 Nm3, and this relationship can be used to convert hydrogen produced from normal cubic meter to kilogram [42]. The calculations have been conducted with regard to the annual energy production of the four wind turbines based on the actual and Weibull data. Table 4 presents the obtained results from the analysis to obtain annual produced hydrogen for the nominated station.

Table 4. Yearly hydrogen production by different wind turbines

	Actual	Weibull
Model	Annual hydrogen production (ton-H_2)	Annual hydrogen production (ton-H_2)
Vestas V47	11.87	11.76
AWE 52-900	15.43	15.23
EWT Directwind 500/54	15.62	15.36
Nordtank-300	5.20	5.09

Clearly, if a EWT Directwind 500/54 model wind turbine be used in this station, the highest amount of hydrogen would be produced if compare all wind turbine models.

The differences between annual hydrogen production from two methods of the actual values and the Weibull can be represented by the percent error. Percent error is the percentage ratio of the measured data and the actual data difference over the actual value. The calculated percent errors of the amount of hydrogen produced from wind energy are in a range of 0.92 to 2.12. The estimated values of hydrogen production of Vestas V47 installed in this site have the minimum percent error, while the wind turbine of Nordtank-300 placed in the station exhibits the greatest difference between obtained results from two used methods.

5. Conclusions

The wind energy potential of Pincher Creek in the province of Alberta in Iran, and the feasibility of using the wind energy to produce hydrogen to meet the energy demand were investigated. Four different wind turbines of Vestas V47, AWE 52-900, EWT Directwind 500/54, and Nordtank-300 were selected for performing the analysis. The obtained outcomes from the assessments can be summarized as follows:

- Two approaches of the actual average wind turbine power and the Weibull were used for this study which the results are almost same.
- EWT Directwind 500/54 model wind turbine exhibits the best capacity factor among all examined turbines with the highest value of 22.05%.
- The best performance in terms of total energy production is also related to EWT Directwind wind turbine with an annual production of 966 MWh.

- According to the wind-hydro conversion system discussed in the previous sections, the amount of hydrogen produced has a direct relationship with the annual wind turbine energy production. Thus, installing the wind turbine of EWT Directwind in this station resulted in the highest yearly hydrogen production capacity of 15.62 ton-H2.

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Biography

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