Research article

Assessment of wind energy potential and economic evaluation of four wind turbine models for the east of Iran

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ABSTRACT

This study examined the potential of wind energy in 22 regions in eastern Iran. In this regard, it investigated the parameters of Weibull, mean wind speed, and wind power density in these areas. The results showed that the mean wind speed was above 4 m/s at all stations and in ten stations was above 5 m/s. Also, the study of monthly wind speed fluctuations in eastern parts of Iran and its comparison with the relevant variations of electricity consumption showed that the fluctuations of speed is clearly in line with the requirements of electrical energy consumption in Iran. In addition, the annual production of energy and the economic performance of four commercial turbine models at 22 sites were investigated.

Generally, Mapna 2.5 MW and Vestas V100–1.8 MW 60 turbines were more efficient than the other two turbine models in terms of annual production of energy and cost of producing electricity.

The results of the economic analysis showed that investment in wind farms in eastern parts of Iran could be associated with high profitability. Finally, the results of this study indicated that planning to exploit wind energy for electricity production in eastern parts of Iran is an appropriate strategy to reduce Iran's dependence on fossil fuels.

1. Introduction

Governments have turned to renewable energy in order to reduce the use of fossil fuels, since fossil fuels play a significant role in global warming and greenhouse gas emissions. Renewable energy is environmentally friendly, low-cost, and sustainable [1]. Renewable energy technologies lead to sustainable economic development and environmental protection [2]. Renewable energy in Iran has been neglected. Iran has 9% world's oil reserves and 17% of the world's natural gas reserves. Due to abundant reserves of fossil fuels, Iran does not show a tendency to find an alternative source of energy [3].

Based on the Iranian Ministry of Energy's annual report, Iran's power generation capacity at the end of 2016 was about 76.428 MW [4]. According to the International Renewable Energy Agency [5], installed capacity of wind energy for Iran was 190.9 MW by 2017. The share of each type of power plant installed in Iran is as follows: steam power plant 21.05%, gas turbine power plant 35.37%, combined cycle plant 25.24%, hydropower plant 15.02%, nuclear plant 1.36%, combined heat and power (CHP) plant 1.06%, renewable fuel plant 0.32%, and diesel engine 0.58% [6].

The Iranian power industry plays a significant role in the production of polluting gas in Iran, due to the high dependency of this industry on fossil fuels. The emissions of carbon dioxide by the Iranian electricity industry in 2016 were more than 152 million tons, according to the Iranian Ministry of Energy's annual report. Also, the NOx and SOx emissions were 233 and 304 thousand tons, respectively [4]. On this basis, it can be said that the Iranian electricity industry is a highly polluting industry that produces a huge amount of greenhouse gases and air pollutants, which have adverse effects on the environment and civilians' health.

Wind energy is converted into electricity by wind turbines. This energy conversion is more energy efficient than other energy conversion systems [7]. A 30% reduction in energy consumption has been a target according to the latest five-year plan of the Islamic Republic of Iran. Iran claims that it has failed to achieve its goal of a 30% reduction over these five years due to international sanctions. Iran has set a target to decrease national annual emissions by 4% by 2030, before the Paris Agreement in November 2015. It is acknowledged that if the sanctions end and the proper support is delivered, Iran will be able to reduce greenhouse gas emissions.
emissions by 8% by 2030. Iran signed the Paris Agreement in April 2016 [8]. High energy demand by an increasing population and the negative impact of fossil fuel economies on climate change have led Iran to consider investment in renewable energies. In this regard, wind energy, a renewable source of energy, is often recommended.

Wind energy resource assessment is technically required as an imperative step in prediction of annual electrical energy production from wind energy at potential locations [9]. It is not only an essential part of the development of wind power utilization, but also provides the investors with the necessary confidence in financial feasibility and mitigating risks [10]. The wind energy potential for a specific location is calculated using detailed wind variables such as direction, speed, availability, and continuity [11, 12]. Different methodologies have been used to study these wind characteristics, such as the Wind Atlas Analysis and Application Program (WAsP), as well as Rayleigh and Weibull methods [12]. Furthermore, based on a timeframe of wind speed data, these properties have been examined at multiple temporal scales (monthly, seasonal, and yearly periods) [13].

Many researchers have investigated the wind energy potential of an area using different methods in different countries. The most common method in wind energy potential research is Weibull distribution. For example, Chandel et al [14] and Solyali et al [15] investigated wind energy potential using the Weibull distribution. Furthermore, Solyali et al [15] used the Weibull distribution, and the WAsP model. Their results showed that the WAsP model was more efficient and provided the highest coefficient of determination (R2). Some studies examined the potential of wind energy over the short and long-term statistical periods by using WAsP. Promsen et al [16] and Nouri et al [17] used wind data over a short statistical period with the WAsP model, and also investigated wind speeds and determined the optimal location for wind turbine installation. Boudi and Guerr [18], Daf and Notton [19], and Sahin et al [20] studied the potential of wind energy by using wind data over a long statistical period and the WAsP model. Sahin et al [20] examined the effect of the roughness of ground for each station. Daf and Notton [19], besides the potential of wind energy, examined the economic performance of four types of turbine models.

A great deal of research in this area has focused on eastern parts of Iran due to the high wind energy potential in this region. Mostafaeipour et al [21], Fazelpour et al [22], and Tizpar et al [23] used the Weibull distribution. Pishgar-Komleh and Akram [24], in addition to the Weibull distribution, used the Rayleigh distribution to investigate the energy potential. Also, Mostafaeipour et al [21] and Fazelpour et al [22] investigated the economic performance of wind energy. Saeidi et al [50] have investigated wind energy potential at four sites in Razavi and North Khorasan in eastern Iran. Penchah et al [51] simulated wind energy parameters in the South Khorasan region in 2007 using the weather research and forecasting (WRF) model. Other researchers identified other windy areas of Iran by using the Weibull distribution. Alamdari et al [49] investigated wind energy potential in 68 sites in 2007 at 10 m, 30 m, and 40 m heights throughout Iran. Keyhani et al [25], examined Tehran, the capital of Iran, and Mirhosseini et al [26] focused on several cities in the Semnan province, including Biajmangd, Damghan, Garm-sar, Semnan, and Shahrood.

In this study, the wind energy potential was assessed for three provinces of Eastern Iran: Khorasan Razavi, South Khorasan, and Sistan and Baluchestan. East and southeast parts of Iran are some of the windiest regions of Iran. The area is affected by powerful winds in the northeast, northwest, under the name Wind Lavar or wind of 120 days [27, 28]. For this reason, various studies have been conducted to evaluate wind energy potential in some regions of eastern Iran [21, 22, 23, 24]. However, a comprehensive evaluation of wind energy potential throughout this windy region has not been done in any of these studies. In addition, the economic evaluation of different wind turbines according to the laws of the Ministry of Energy of Iran has not been considered in any of these studies.

In this study, by using data from all Wind Measurement Towers (WMTs) in eastern Iran, the wind energy potential of this region has been studied comprehensively. The wind data from 22 WMTs belonging to the Iranian Ministry of Energy, which record wind direction and wind speed data every 10 min, were used. The Weibull distribution was calculated by using WAsP. Then, an evaluation of wind characteristics, wind power density, and wind energy density were obtained. In the next step, technical and economic analysis and the use of four commercial turbine
models, according to the rules and conditions of Iran, were investigated. Unlike previous studies, the present study is a comprehensive evaluation of wind energy potential in eastern Iran and the information in this study will be helpful for the government and any organization that intends to invest in wind energy sources in this part of Iran.

2. Description of location and data

This article studied the potential of wind energy and its economic value in the Khorasan Razavi, South Khorasan, and Sistan and Baluchestan provinces. Khorasan Razavi is located in the northeast of Iran. It is bordered by Turkmenistan to the north and northeast, by Afghanistan to the east, by the province of South Khorasan to the south, and by the province of Semnan to the west. Khorasan Razavi is located at the longitude of 56° to 61°E and latitude of 33° to 37°N [29].

The South Khorasan province is located in the east of Iran. It borders Khorasan Razavi to the north and Sistan and Baluchestan to the south. South Khorasan is surrounded by mountains and mountains on four sides [30].

The Sistan and Baluchestan province is located in southeastern Iran. This province is located at the longitude of 58° to 63°E and the latitude of 25° to 31°N. It is bordered by South Khorasan and Afghanistan to the north, with Pakistan and Afghanistan to the east, and by the provinces of Hormozgan and Kerman and the Gulf of Oman to the west [31]. The province consists of two parts, Sistan in the north and Baluchestan in the south [22]. This province has seasonal winds with different directions, the most important of which is known as the wind of 120 days of Sistan [21]. A wind turbine with a capacity of 660 kW is currently located in the city of Zabol in the Sistan and Baluchestan province. Preliminary observations indicate that there is a greater potential for wind in the area that the Iranian government has not harnessed. The province is among the poorest and most undeveloped provinces of Iran [24].

Data from 22 WMTs belonging to the Iranian Ministry of Energy, which record wind direction and wind speed data every 10 min [32] were used in this study. The characteristics of these WMTs are presented in Table 1. Also, Figure 1 presents the study area and the location of each WMT.

![Figure 1](image1.png)

**Figure 1.** Geographic locations of the Wind Measurement Towers (WMTs) and the study area. The location of the WMTs are numbered according to Table 1.

![Figure 2](image2.png)

**Figure 2.** Steps for calculating output power of wind turbines using WASP software.
3. Methodology

In this study, WAsP software was used to analyze the potential of wind energy. Using this software, the performance of four commercial wind turbine models for Khorasan Razavi, South Khurasan, and Sistan and Baluchestan provinces were measured. Figure 2 presents the process of using WAsP software to analyze potential of wind energy and calculating wind turbines’ output power. Also, a cost analysis model was used for economic evaluation of the selected turbines.

3.1. Wind analysis model

WAsP uses the Weibull function to calculate the frequency distribution of wind speeds across time. The following equation is used to define it:

\[
f(v) = \left( \frac{K}{\lambda} \right)^k \left( \frac{v}{\lambda} \right)^{k-1} \exp \left( -\left( \frac{v}{\lambda} \right)^k \right) \quad (v > 0, k, A > 0)
\]  

(1)

where \(f(v)\) is the probability of observed wind speed \(v\). \(K\) denotes the Weibull scale parameter \((\text{m/s})\). The corresponding cumulative distribution function can be described as given in the equation below [33]:

\[
f(v) = 1 - \exp \left( -\left( \frac{v}{\lambda} \right)^k \right) \quad (v > 0, k, A > 0)
\]  

(2)

3.2. Wind power density

The power of the wind that flows at a speed of \(v\) through a blade sweep area of \((Sw)\) can be expressed by the following equation.

\[
P(v) = \frac{1}{2} Sw \rho v^3
\]  

(3)

where \(\rho\) is the air density.

The wind power density of a site based on a Weibull probability density function can be expressed by the following equation [34]:

\[
P = \frac{1}{2} \rho A^3 f \left( 1 + \frac{3}{K} \right)
\]  

(4)

3.3. Wind energy density

Wind energy density can be estimated by knowing the wind power. The following equation is used for calculation wind energy density in a desired time, \(T\) [35]:

\[
\frac{E}{S_w} = \frac{1}{2} \rho A^3 f \left( 1 + \frac{3}{K} \right) T
\]  

(5)

3.4. Vertical extrapolation of mean wind speed

There have been various mathematical models created to describe the vertical profile of wind speed. The Logarithmic law [36] was used to compute the average wind speed \(V\) at height \(Z\) on WAsP. This method, which solely depends on the roughness \(Z_0\) in the situation of neutral stability, is an analytical model that is commonly used to determine the vertical wind profile. The following equation [37] describes this method, which is only valid close to the ground over a relatively flat field:

\[
\frac{V_i}{V_0} = \left( \frac{Z_i}{Z_0} \right)^{-a}
\]  

(6)

where \(a\) is a coefficient, more precisely the Hellmann exponent, which varies between 0.1 and 0.4, depending on the roughness of the terrain [17].

3.5. Wind turbine energy production

If \(Ui\) is the average wind speed over the time interval from time \(ti\) to \(ti + \Delta t\), then over a period of \(N\) observations, the average power that can be generated by that turbine is expressed as:

\[
P_{w} = \frac{1}{N} \sum_{i=1}^{N} P_{w}(Ui)
\]  

(7)

where \(P_{w}(Ui)\) is the power output defined by the turbine power curve. Hence, the energy yield from a wind turbine can be expressed as [38]:

\[
E = \sum_{i=1}^{N} Pw(Ui) \Delta t
\]  

(8)

If \(P_{R}\) is the rated power of the turbine, and CF is the capacity factor, the energy generated (EI) by the turbine in a year is:

\[
E_{i} = 8760 \times P_{R} \times CF
\]  

(9)

Capacity factor, which is a measure of electrical energy generated per kW of installed capacity (kW h/kW) per year, would primarily depend on the wind speed distribution and the design of the wind turbine [26, 39].

3.6. Energy cost analysis

There are several methods to estimate the cost of wind turbines. The present value cost (PVC) method was used to evaluate the cost of wind energy produced in this study. The PVC was calculated by using the following equation:

\[
PVC = I + Comr \sum \left[ \frac{1+i}{1+r} \right] \times \left[ 1 - \left( \frac{1+i}{1+r} \right)^n \right] - S \left( \frac{1+i}{1+r} \right)^n
\]  

(10)

The cost calculation was performed on the basis of the following assumptions [40]:

- The estimated lifetime of a turbine \((t)\) is 20 years.
- The interest rate \((r)\) and inflation rate \((\bar{I})\) are 15% and 18.4%, respectively [41].
- Operation, maintenance, and repair cost \((C_{ort})\) is 25% of the machine cost/lifetime.
- Scrap value \((S)\) is taken as 10% of the cost of the turbine and civil work.
- Investment cost \((I)\) includes the turbine price plus 20% for the construction work, the connection cables to the grid, and other setup costs. Also, a 9% value-added tax to be paid to the government should be added to this amount. At the same time, the use of foreign turbines is associated with other costs, such as 5% customs duties and 8% sea transport [32].

The cost per kW h of electricity generated (UCE) can be expressed by the following equation [13, 42]:

\[
UCE = \frac{PVC}{AEF} \frac{\$}{kWh}
\]  

(11)

4. Results and discussions

4.1. Wind data characteristics

Previous research has found that wind statistics findings are nearly the same in various years [43, 44, 45], implying that wind data for a whole year may be used to establish the parameters of the Weibull probability distribution function and to estimate the wind energy potential [46]. To analyze the wind energy potential in this study, wind data recordings for a whole year (for a period of 12 consecutive months) were chosen from the 22 WMTs. The mean wind speed, wind power
site Wind Mean Speed (m/s) Power Density (W/m²) Weibull-K Height m
Rodab 5.74 241 6.4 1.67 40
Qadamgah 4.91 207 5.3 1.33
Jargal 4.74 113 5.3 1.95
Sarakhs 4.71 159 5.2 1.53
Bardeskan 4.22 109 4.6 1.45
Davarzan 4.03 143 4.3 1.20
Dashtebayaz 4.18 106 4.6 1.45
Khaf 10 1090 11.3 1.83
Fadshak 6.22 227 7 2.08
Nehbandan 5.22 279 5.6 1.24
Afriz 5.20 186 5.8 1.55
Milnader 6.92 491 7.7 1.53
Shandol 6.72 397 7.5 1.67
Lottak 7.01 437 7.9 1.71
Nosratabad 5.06 128 5.07 1.92
Chabahar 5.43 156 6.1 2.29
Mirjave 4.98 141 5.6 1.78
Zahedan 4.74 155 5.2 1.46
Dhak 4.45 127 4.9 1.48
Khash 4.66 126 5.2 1.60
Delgan 4.44 128 4.9 1.53
Saravan 6.48 227 7.3 2.38
Khaf 11.18 1452 12.6 1.94
Fadshak 7.19 331 8.1 2.24
Nehbandan 6 365 6.5 1.35
Afriz 6.11 368 6.8 1.69
Milnader 7.86 657 8.8 1.63
Shandol 7.71 545 8.7 1.80
Lottak 8.04 601 9.1 1.85
Nosratabad 5.95 187 6.7 2.13
Chabahar 6.34 228 7.1 2.53
Mirjave 5.85 207 6.6 1.94
Zahedan 5.57 218 6.2 1.60
Dhak 5.23 184 5.8 1.60
Khash 5.49 182 6.2 1.76
Delgan 5.22 185 5.8 1.66
Saravan 6.39 218 7.2 2.37
Rodab 6.78 356 7.6 1.81 85
Qadamgah 5.77 293 6.4 1.44
Jargal 5.66 173 6.4 2.18
Sarakhs 5.43 209 6.1 1.72
Bardeskan 5.04 160 5.6 1.60
Davarzan 4.78 199 5.2 1.31
Dashtebayaz 4.99 156 5.6 1.60
Khaf 11.28 1487 12.7 1.95
Fadshak 7.42 352 8.4 2.30
Nehbandan 6.08 375 6.6 1.35
Afriz 6.19 277 6.9 1.71
Milnader 7.95 675 8.9 1.63
Shandol 7.80 560 8.8 1.81

Table 2 (continued)

| Site       | Wind Mean Speed (m/s) | Power Density (W/m²) | Weibull-K Height m |
|------------|-----------------------|----------------------|--------------------|
| Lottak     | 8.14 619 9.2 1.86     |
| Nosratabad | 6.03 194 6.8 2.15     |
| Chabahar   | 6.43 236 7.2 2.56     |
| Mirjave    | 5.93 214 6.7 1.96     |
| Zahedan    | 5.65 225 6.3 1.61     |
| Dhak       | 5.31 190 5.9 1.61     |
| Khash      | 5.57 188 6.3 1.78     |
| Delgan     | 5.29 191 5.9 1.67     |
| Saravan    | 6.48 227 7.3 2.38     |

The primary reason for the high consumption of electricity in the warm period of the year compared to the cold season in Iran is the high temperature of the air and the use of cooling devices by consumers. Seasonal fluctuations in wind power in eastern Iran are clearly consistent with the needs of electric power consumption in Iran, due to the increase in electric power consumption in the spring and summer compared to autumn and winter.

Figure 5 presents the Wind direction radar charts of all the sites. The distribution of wind direction in all the sites is largely different. The variation of direction is very low in nine sites (Fadshak, Afriz, Jargal, Qadamgah, Rodab, Khaf, Lottak, Shandol, and Milnader), and the wind direction at each of these sites is suitable for wind energy projects. The reason is that, due to little variation in wind direction, only a small amount of energy is lost in wind turbines [48]. In contrast, the wind direction variations of seven sites (Delgan, Zahedan, Chabahar, Nosratabad, Saravan, Mirjaveh, and Davarzan) are relatively high.

Figure 6 presents the mean daily wind speed at the studied sites. At most sites, the maximum wind speed was observed throughout the day in the afternoon and early hours of the night, while the wind speed reaches its minimum in the early hours of the morning. The daily wind fluctuations at five sites in Saravan, Rodab, Lottak, Shandol, and Milnader are different from other sites. Wind speed at these sites was lowest in the afternoon and early hours of the night.

4.2. Electricity generation and cost analysis

Four turbine models were selected in this study, with capacity between 660 kW and 2.5 MW, and height between 40 m and 85 m Table 4 presents the main characteristics of the selected wind turbines. S47-660
Table 3. Seasonal mean wind speed at 40, 80, and 85 m above ground.

| Site            | Spring | Summer | Fall | Winter | Height m |
|-----------------|--------|--------|------|--------|----------|
| Rodab           | 5.87   | 8      | 5.6  | 4      | 40       |
| Qadamgah        | 5.73   | 6.9    | 4.8  | 3.4    |          |
| Jangal          | 4.97   | 5.4    | 4.6  | 4.2    |          |
| Sarakhs         | 4.83   | 5.4    | 4.1  | 4.9    |          |
| Bardeskan       | 4.37   | 4.9    | 3.4  | 4.5    |          |
| Davarzan        | 4.5    | 5.9    | 3.6  | 3.2    |          |
| Dashtebayaz     | 3.93   | 5.7    | 3.1  | 2.9    |          |
| Khaf            | 8.27   | 14.9   | 8.9  | 6.2    |          |
| Fadshak         | 5.5    | 8.8    | 6.2  | 4.3    |          |
| Nehbandan       | 3.8    | 4.6    | 4.1  | 3.3    |          |
| Afriz           | 5.23   | 8.5    | 4.8  | 2.8    |          |
| Milnader        | 6.72   | 11     | 6.2  | 4.7    |          |
| Shandol         | 5      | 9.3    | 8    | 4.9    |          |
| Lottak          | 6.83   | 10.6   | 6    | 4.2    |          |
| Nosratabad      | 5.63   | 5.5    | 4.2  | 4.9    |          |
| Chabahar        | 6.77   | 5.5    | 4.7  | 5      |          |
| Mirjave         | 4.53   | 5.6    | 4.7  | 3.7    |          |
| Zahedan         | 4.37   | 4.8    | 5.4  | 4.1    |          |
| Dhak            | 4.73   | 4.6    | 4.2  | 4.3    |          |
| Khash           | 4.97   | 4.9    | 3.8  | 4.9    |          |
| Delgan          | 4.6    | 5.2    | 4.2  | 3.8    |          |
| Saravan         | 6.53   | 5.9    | 4.5  | 5      |          |
| Rodab           | 6.8    | 9.3    | 6.5  | 4.7    | 80       |
| Qadamgah        | 6.6    | 8.0    | 5.6  | 3.9    |          |
| Jangal          | 5.9    | 6.4    | 5.4  | 4.9    |          |
| Sarakhs         | 5.5    | 6.1    | 4.7  | 5.6    |          |
| Bardeskan       | 5.1    | 5.8    | 4.0  | 5.3    |          |
| Davarzan        | 5.3    | 6.9    | 4.2  | 3.7    |          |
| Dashtebayaz     | 4.6    | 6.7    | 3.6  | 3.4    |          |
| Khaf            | 9.2    | 16.7   | 10.0 | 6.9    |          |
| Fadshak         | 6.7    | 9.9    | 7.2  | 5      |          |
| Nehbandan       | 4.4    | 5.3    | 4.7  | 3.8    |          |
| Afriz           | 6.1    | 10.0   | 5.6  | 3.3    |          |

Table 3 (continued)

| Site            | Spring | Summer | Fall | Winter | Height m |
|-----------------|--------|--------|------|--------|----------|
| Milnader        | 7.6    | 12.5   | 7.0  | 5.3    |          |
| Shandol         | 5.7    | 10.7   | 9.2  | 5.6    |          |
| Lottak          | 7.8    | 12.2   | 6.9  | 4.8    |          |
| Nosratabad      | 6.6    | 6.5    | 4.9  | 5.8    |          |
| Chabahar        | 7.9    | 6.4    | 5.5  | 5.8    |          |
| Mirjave         | 5.3    | 6.6    | 5.5  | 4.3    |          |
| Zahedan         | 5.1    | 5.6    | 6.3  | 4.8    |          |
| Dhak            | 5.6    | 5.4    | 4.9  | 5.1    |          |
| Khash           | 5.9    | 5.8    | 4.5  | 5.8    |          |
| Delgan          | 5.4    | 6.1    | 4.9  | 4.5    |          |
| Saravan         | 7.7    | 7.0    | 5.3  | 5.9    |          |
| Milnader        | 7      | 9.4    | 6.6  | 4.7    | 85       |
| Qadamgah        | 7      | 8.1    | 5.6  | 4.0    |          |
| Jangal          | 6      | 6.4    | 5.5  | 5.0    |          |
| Sarakhs         | 6      | 6.2    | 4.7  | 5.6    |          |
| Bardeskan       | 5      | 5.9    | 4.1  | 5.4    |          |
| Davarzan        | 5      | 7.0    | 4.3  | 3.8    |          |
| Dashtebayaz     | 5      | 6.8    | 3.7  | 3.5    |          |
| Khaf            | 9      | 16.8   | 10.0 | 7.0    |          |
| Fadshak         | 7      | 10.5   | 7.4  | 5.1    |          |
| Nehbandan       | 4      | 5.4    | 4.8  | 3.8    |          |
| Afriz           | 6      | 10.1   | 5.7  | 3.3    |          |
| Milnader        | 8      | 12.6   | 7.1  | 5.4    |          |
| Shandol         | 6      | 10.8   | 9.3  | 5.7    |          |
| Lottak          | 8      | 12.3   | 7.0  | 4.9    |          |
| Nosratabad      | 7      | 6.6    | 5.0  | 5.8    |          |
| Chabahar        | 8      | 6.5    | 5.6  | 5.9    |          |
| Mirjave         | 5      | 6.7    | 5.6  | 4.4    |          |
| Zahedan         | 5      | 5.7    | 6.4  | 4.9    |          |
| Dhak            | 6      | 5.5    | 5.0  | 5.1    |          |
| Khash           | 6      | 5.9    | 4.5  | 5.9    |          |
| Delgan          | 5      | 6.2    | 5.0  | 4.5    |          |
| Saravan         | 8      | 7.1    | 5.4  | 6.0    |          |
and Mapna 2.5 MW turbines are produced in Iran, while Vestas V90–2.0 MW GridStreamer and Vestas V100–1.8 MW 60 Hz VCS turbines are made outside Iran.

Table 5 indicates energy production (GWh/year), capacity factor, and electricity cost ($/kWh) for four wind turbines. The annual energy output varies depending on the location and model of the turbines. Among the

Figure 4. Monthly mean electricity consumption of Iran in 2016 [4].

Figure 5. Wind direction radar charts at the a) Fadshak_Nehbandan_Milnader_Afriz, b) Bardeskan_Davarzan_Dashtebayaz_Khaf, c) Rodah_Qadamgah_Saravan_Sarakhs, d) Shandol_Nosratabad_Chahabar_Mirjave, e) Zahedan_Dhak_Khash_Lottak, f) Delgan_Jangal
sites, the largest annual energy production is 11.98 GWh in Khaf and is obtained from a Mapna 2.5 MW turbine. The lowest annual energy production is 0.561 GWh in Dashtebayaz and is obtained with an S47-660 turbine. In general, the annual energy production and the capacity factor of each of the four turbine models at the Khaf, Fadshak, Lottak, and Milnader sites are higher than at other sites. Investigating the turbine capacity factor shows that among the four studied turbine models, the Vestas V100–1.8 MW 60 Hz VCS turbine has the best performance, while the S47-660 turbine (Sabaniroo) has the weakest performance.

Also, the Mapna 2.5 MW turbine has the best performance in the annual production of energy among the other turbines. Based on the results of the economic analysis, the lowest cost of wind power generation among the studied sites is 0.015 USD/kWh at the Khaf site and with the Mapna 2.5 MW turbine. The highest wind power cost in all of the sites is 0.085 USD/kWh at the Dashtebayaz site and with the S47-660 turbine (Sabaniroo). The cost of generating electricity using the Mapna 2.5 MW and Vestas V100–1.8 MW 60 Hz VCS turbines is less than two other turbine models in most sites. In general, Mapna 2.5 MW and Vestas V100–1.8 MW 60 Hz VCS turbines have a better performance than the two other turbine models.

The average cost of generating a kilowatt of electricity in Iran in 2016 was $0.027, according to Iran’s Ministry of Energy report. The reason for the low cost of producing electricity in Iran is the very cheap subsidized fuel provided to fossil fuel power plants by the government. For example, the price per cubic meter of gas for the fossil fuel power plants is $0.0012 [4]. It can be concluded that despite the huge subsidies provided to fossil fuel power plants, wind power produced in some parts of eastern Iran is quite competitive with fossil fuel plants in terms of price. The guaranteed purchase price of wind farm production by the Iranian government is 0.08 USD/kWh for wind farms with a capacity of more than 50 MW and 0.1 USD/kWh for wind farms with a capacity of less than 50 MW.

In the case of wind turbines that are produced in Iran and used for the construction of wind power plants, the guaranteed purchase price of electricity by the government will increase. In the case of using Iranian turbines, according to the percentage of Iranian parts used in producing wind turbines, the guaranteed purchase price of electricity by the government will increase by 30% [32]. Overall, investing in small and large

![Figure 6. Diurnal means wind speed at the a) Sarakhs_Khaf_Fadshak_Chabahar_Lottak_Milnader, b) Nehbandan_ShandoNosratab_Mirjave_Zahedan_Dahak, c) Rodah_Qadamgah_Jangal_Dashtebayaz_Bardeskan_Davarzan, d) Afriz_Khash_Delog_Saravan](image)

Table 4. Main characteristics of the selected wind turbines.

| Model                | Vestas V100–1.8 MW 60 Hz VCS | Vestas V90–2.0 MW GridStreamer | Mapna 2.5 MW | S47-660 (Sabaniroo) |
|----------------------|-------------------------------|-------------------------------|--------------|---------------------|
| Rated capacity (kw)  | 1,800                         | 2,000                         | 2,500        | 660                 |
| Rotor diameter (m)   | 100                           | 90                            | 104          | 47                  |
| Hub height (m)       | 80                            | 80                            | 85           | 40                  |
| Cut in speed (m/s)   | 4                             | 4                             | 3.5          | 4                   |
| Rate Speed (m/s)     | 12                            | 13                            | 12           | 15                  |
| Cut out Speed (m/s)  | 20                            | 25                            | 25           | 25                  |
| Swept area (m²)      | 7850                          | 6362                          | 8495         | 1734.9              |
| Price ($)            | 2294000                       | 2563000                       | 2548000      | 660000              |
wind farms in eastern Iran, particularly on the sites of Khaf, Afriz, Lottak, Shandol, Milnader, Fadshak, and Chabahar, can be highly profitable due to the guaranteed electricity purchase prices.

5. Conclusions

In this study, wind energy potential and economic analysis in 22 WMTs in eastern Iran were investigated for the first time. In addition, the technical and economic performance of four commercial turbine models designed to generate electricity were studied according to the Iranian rules and conditions on these sites. It is noteworthy that two of these models are produced in Iran. The following results were obtained based on this study.

- The wind speed at 40 m above ground level at all stations studied is higher than 4 m/s, and at 10 stations it is above 5 m/s. The highest wind speed is at Khaf Station, with 9.8 m/s.
- In almost all sites, the wind speed during the warm period of the year (April to September) is higher than the wind speed during the cold period of the year (October to March). As a result of the increase in electric energy consumption in the spring and summer compared to autumn and winter, monthly fluctuations of wind speed in eastern Iran is clearly consistent with the electricity consumption requirements in Iran.
- In most sites, the maximum wind speed is observed during the day, in the afternoon, and early at night, while the minimum wind speed is observed in the early hours of the morning.
- Annual energy production and the capacity factor of all four turbine models at the sites of Khaf, Lottak, Shandol, Milnader, Fadshak, and Chabahar, can be highly profitable.
- The results of the economic analysis showed that investments in the construction of small and large wind farms in eastern Iran could be associated with high profitability, considering the guaranteed energy purchasing prices in Iran.
- The cost of producing wind power in some parts of eastern Iran is quite competitive with the cost of generating electricity from fossil fuel power plants, despite the many subsidies the government provides for power generation from fossil fuel power plants.
- An attempt to exploit wind energy in order to generate electricity in eastern parts of Iran is a suitable strategy in order to reduce the dependence of Iran's power industry to fossil fuels, according to the findings of this research.

Declarations

Author contribution statement

Hossein Mohamadi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.
Alireza Saeedi: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Shahla Veisi: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Saeid Sepasi Zangabadi & Shaha Veisi: Performed the experiments; Contributed reagents, materials, analysis tools or data.

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Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.
Additional information

No additional information is available for this paper.

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