

# A comparative study of different wind speed distribution models for accurate evaluation of onshore wind energy potential: A case study on the southern coasts of Iran

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## Abstract

Wind power output is highly dependent on the wind speed at the selected site, therefore wind-speed distribution modeling is the most important step in the assessment of wind energy potential. This study aims at accurate evaluation of onshore wind energy potential in seven coastal cities in the south of Iran. Six Probability Distribution Functions (PDFs) were examined over representative stations. It has been deduced that the Weibull function, which was the most used PDF in similar studies, was only applicable to one station. Here, Gamma offered the best fit for three stations and for the other ones, Generalized Extreme Value (GEV) performed better. Considering the ranking of six examined PDFs and the simplicity of Gamma, it was identified as the effective function in the southern coasts of Iran bearing in mind the geographic distribution of stations. Besides, six turbine power curve functions were contributed to investigate the capacity factor. That was very important, as using only one function could cause under- or over-estimation. Then, stations were classified based on the National Renewable Energy Laboratory system. Last but not least, examining a range of wind turbines enabled scholars to extend this study into the practice and prioritize development of stations considering budget limits.

**Keywords:** Wind power; Wind energy; Coastal regions; Statistical distributions; Wind turbine capacity factor

## 1. Introduction

Renewable energies are harnessed in various types such as wind power, solar power, biopower, geothermal power, and ocean power. All these types, except geothermal and ocean energy, originate from the infinite energy of the sun, which emits the power about  $1.74 \times 10^{17}$  W [1]. About 1-2 percent of this energy is transformed into the wind energy; as an interminable, environment-friendly, clean and reliable source; which is 50-100 times higher than energy conversion from all the plants in the earth combined [2]. It is estimated that the global wind energy potential is about 10 million MW, which could fulfill 35% of the total demand for world energy [3]. The cumulative global installed capacity of the wind energy was 539,581 MW in 2017 [4], and it is forecasted that the global wind capacity will reach 800,000 MW by 2021 [5]. In another study, it was estimated that the wind share of electricity generation will rise from 3.5% in 2015 to 36% in 2050 [6]. The initial goal of this study is to provide a comprehensive technical assessment of wind energy resources. This helps engineers, scholars, and policymakers to decide for optimal investment with maximum profits. Scholars and practitioners in the future could use the results of the current study as inputs for further economic analyses. Wind resource assessment is being conducted in seven coastal stations; including Abadan, Mahshahr, Bordekhoon, Delvar, Kish, Jask, Chabahar and the results are compared against the similar studies. This study is structured as follows. In Section 1.1 an overview of the wind energy in Iran is provided. Section 1.2 presents a literature review of the wind energy potential assessment in Iran. Section 2 depicts the area of study and characteristics of the sites. Section 3, explains the methodology used in the study, statistical distributions, determining wind power and energy density and capacity and availability factors of different wind turbines. Section 4 describes case studies and results of the study by using different statistical distributions across all stations and wind power and energy density.

### 1.1. Wind energy in Iran

Although Middle East countries are rich in conventional energy sources such as oil and natural gas, industrialization and environment impacts have encouraged their policy-makers to invest in renewable energies. Iran with a population of 79.2 million and an area of 1,648,195 km<sup>2</sup> (about half of this area is habitable) largely depends on fossil fuels such as crude oil in its energy sector [7]. Now, there is a considerable consumption of traditional energy resources in Iran because of the large amount of low-cost fossil fuels. This exacerbated the misuse of energy in industrial, transportation, and home sectors resulting in various environmental problems. The situation compelled energy policymakers to move toward renewable energies in the country [7]. The average growth rate of energy consumption and generation in Iran is 4% and 2%, respectively and therefore, it is expected that Iran increasingly will need to provide a great share of its energy demand from renewable energy sources in years ahead, to meet future rising energy demand [9]. As set out in the 6<sup>th</sup> national development plan of the country, the Iranian government has the target of extracting 5000 MW from renewable energy resources by 2020 [10].

However, Iran has a great potential for solar energy production because of its dry and warm climate. Without industrial infrastructures to produce solar panels and difficulty in import materials and resources because of political conditions, starting large-scale solar power would be expensive and time-consuming. With these challenges, governments have drawn their attention to a more practical and accessible solution: Wind power. In 1994, the first wind turbine was installed in Iran at Manjil. After that, various efforts were made to increase the wind electricity generation in Manjil such as the construction of 25MW and 60MW power stations. In 2018, the total installed capacity of Iran's wind energy reached 280 MW. According to the Ministry of Energy reports, Iran planned to reach a 4500MW goal in wind energy capacity in 2023 [11]. Although wind energy shares 43% of Iran's electricity production based on renewable energies (greatest among all other types) [12], as shown in **Error! Reference source not found.**, there is a lack of installed wind capacity in Iran's energy resources especially in southern coastal regions regarding their area and population.

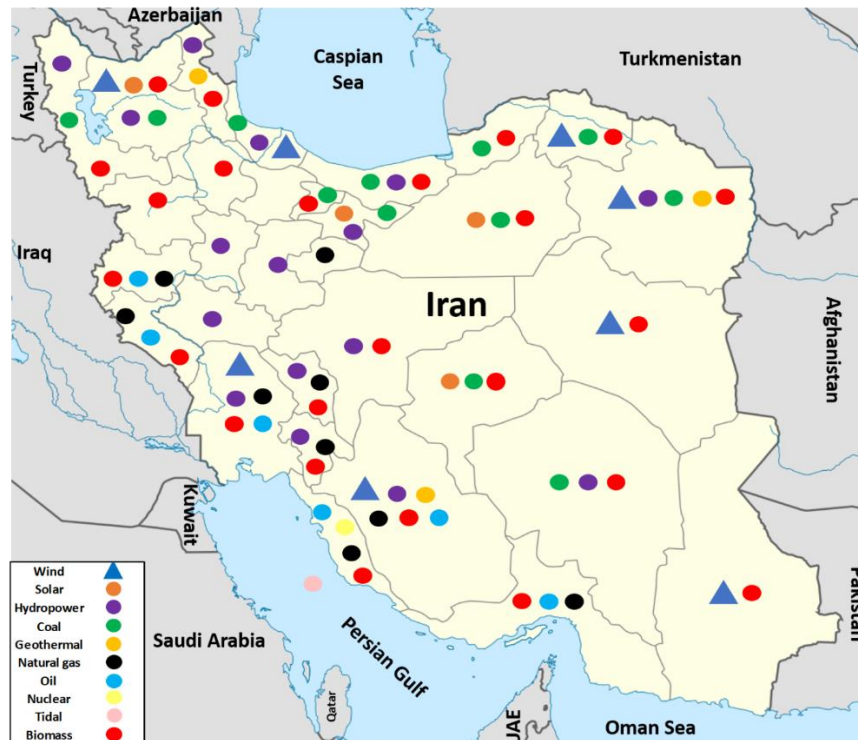


Figure 1 Energy resources in Iran [13]

## 1.2. Review of the literature

Wind power is mainly dependent on wind speed. Therefore, a reliable and accurate model for wind-speed data is a solid pavement for investigating wind energy potential. Numerous models have been used in the scientific literature (Sec. 3.1) and among of them, Weibull is the most widely used distribution. However, all regions and their wind patterns cannot be modeled accurately by Weibull. There are numerous alternative distributions namely Gamma, Lognormal, Rayleigh, Nakagami, Gumbel, Burr, Generalized Extreme Value (GEV), Inverse Gaussian (IG), and etc. Hence, in this study, different distributions (Weibull, Gamma, Rayleigh, GEV, IG, and Lognormal) are employed in order to find the most suitable model for wind-speed data based on goodness of fit criteria.

There are many studies for Wind Resource Assessment (WRA) in Iran. In the past decade (from 2010 to 2019), 28 researches related to the wind energy assessment in Iran gained more attention and citation. Table 1 presents distribution function, method of estimation of parameters and the location in each study. Weibull was the most commonly used statistical distribution for describing wind speed data in such studies. In most of them (about 80%), authors did not provide any further statistical investigations for selecting a suitable wind speed distribution, and just used Weibull based on frequent usage while enjoying its simplicity. Besides, there are a few studies in the coastal regions of Iran and most of them are for inland stations. Thus, a comparative study on the effectiveness of different wind speed distributions in the coastal stations is of great importance. In some of these studies performed statistical investigations to select the distribution or the method of estimation of parameters. For example, Mohammadi and Mostafaeipour used Weibull distribution for their study in Zarrineh city and calculated its parameters using two methods; standard deviation method and power density method [14]. They reported that power density method is better estimation method than standard deviation method in monthly, seasonal, and yearly wind pattern.

Nedaei et al. compared performances of four distribution functions (Weibull, Lognormal, Rayleigh, Logistic) in Mahshahr station [15]. They found that the Weibull distribution is the best function to model the wind data in Mahshahr, at two heights of 40 m and 10 m. They also used three different methods (graphical method, maximum likelihood, method of moments) for calculating Weibull parameters. The results show that Graphical method at 10m and method of moments at 40m height are the best methods for calculating Weibull parameters in this city.

Alavi et al. investigated four different distribution functions (gamma, lognormal, Rayleigh, Weibull) for five cities in Kerman province (Bam, Bardsir, Arzuiyeh, Rafsanjan, Shahrabak) [16]. They also used two methods for calculating Weibull parameters; maximum likelihood and method of moments. Results show that the lognormal function produces better results for the actual data, while the Weibull model gives a better fit for the truncated wind speed data. They also concluded that calculating Weibull parameters using MLE performs perfectly well in comparison with MM estimations.

Alavi et al. utilized eight PDFs (exponential, Weibull, gamma, lognormal, log-logistic, inverse-Gaussian, generalized extreme value, Nakagami) in their study and computed the parameters using MLE for wind speed distribution in cities of Chabahar, Khaf, Lutak, Rafsanjan and Zabol [17]. They found that Nakagami performs better than other distributions; however, because of the close performance of the Nakagami and Weibull distributions, they finally proposed Weibull due to its flexibility and widely use.

Nedaei et al. (2016) employed graphical method, Maximum likelihood, and Method of moments to estimate Weibull coefficients in a coastal area in the south of Iran in Gulf of Oman [18]. The author asserted that maximum likelihood method is the best algorithm to estimate Weibull parameters. Although the resulted output for the designated site is not considerable, more studies should be conducted for onshore wind power assessment in Iranian waters, Persian Gulf and Caspian Sea.

Faghani et al. used Weibull because of its widely used for WRA in 35 wind stations in nine provinces [19]. But, for calculation of Weibull parameters three different methods were used; including standard deviation method, empirical method of Lysen, power density method. Based on their investigations, they concluded that the power density method is the most accurate method for extrapolating wind characteristics.

In a more comprehensive study, Nedaei et al. (2018) fitted 46 different PDF and suggested that Wakeby performs better than other distribution functions [20]. They did not mention the method of estimating parameters. The distribution analysis is provided for only the 10 most efficient PDFs, but details about the methodology for selecting these functions among others are not presented in the context of paper.

**Table 1 Comprehensive literature review for wind energy assessment**

Year	Ref.	Distribution (s)	Method of estimation	Case Study Location	Coastal city?
2010	[21]	Weibull	Method of Moments	Tehran city	No
2011	[22]	Weibull	Empirical method	North and South Khorasan provinces	No
2011	[23]	Weibull	Empirical method	Semnan province	No
2011	[24]	Weibull	Method of Moments	Sharbabak city	No
2012	[25]	Weibull	Not mentioned	Abadan city	Yes
2013	[26]	Weibull	Empirical method	Kish and Jask regions	Yes
2013	[27]	Weibull	standard deviation method	Kerman province	No
2013	[28]	Weibull	Not mentioned	Binalood city	No
2013	[29]	Weibull	standard deviation method	Aligoodarz city	No
2013	[14]	Weibull	Standard deviation method Energy pattern factor method	Zarrineh city	No

Year	Ref.	Distribution (s)	Method of estimation	Case Study Location	Coastal city?
2014	[15]	Weibull, Lognormal, Rayleigh, Logistic	graphical method, Maximum likelihood, Method of moments	Mahshahr city	Yes
2014	[30]	Weibull	standard deviation method	Mil-E Nader region	No
2014	[31]	Weibull	Empirical method	Chabahar, Kish and Salafchegan	Yes
2014	[32]	Weibull	Empirical method	Zahedan city	No
2015	[33]	Weibull	Method of Moments	Firouzkooch city	No
2015	[34]	Weibull	Method of Moments	Tabriz and Ardabil cities	No
2016	[17]	gamma, lognormal, Rayleigh, Weibull	Maximum likelihood, Method of moments	Bam, Bardsir, Arzuiyeh, Rafsanjan, Shahrabak	No
2016	[35]	Weibull	Not mentioned	Kahnuj city	No
2016	[36]	Exponential, Weibull, Gamma, Lognormal, Log-Logistic, Inverse-Gaussian, Generalized extreme value, Nakagami	maximum-likelihood	Chabahar, Khaf, Lutak, Rafsanjan and Zabol cities	Yes (Chabahar)
2016	[37]	Weibull	standard deviation method	Asaluyeh, Bordkoon, Delvar, Haft-Chah	Yes
2016	[18]	Weibull	graphical method, Maximum likelihood, Method of moments	Gulf of Oman	Yes
2017	[38]	Weibull	maximum likelihood	Chabahar, Dehak and Dalgan	Yes (Chabahar)
2017	[39]	Weibull	Not mentioned	Fars province	No
2017	[3]	Weibull	standard deviation method	Zabol, Zahak, Zahedan and Mirjaveh cities	No
2018	[19]	Weibull	Standard deviation method, Empirical method of Lysen, Power density method	Nine central provinces	No
2018	[40]	Weibull	standard deviation method	provinces of East Azerbaijan, West Azerbaijan and Ardabil	No
2018	[20]	46 different functions	Not mentioned	Shurje region, Qazvin Province	No
2019	[41]	Weibull	Empirical method	Lotak and Shandol	No



2. Area of interest

For the purpose of the current study seven coastal stations are selected and investigated (Figure 2). The reason for selecting these stations is that in the first place, the Renewable Energy and Energy Efficiency Organization of Iran (SATBA) has provided public access to validated wind speed and direction data for several stations in Iran [42]. Some of these stations are nearshore and some are not. Since the case study has been on the southern coasts of Iran, which comprises 4 provinces: Sistan and Baluchestan, Hormozgan, Bushehr and Khuzestan, in each of these provinces, the nearshore stations with available validated information are selected to cover the whole southern shoreline of Iran from east to west. Hence, these stations have been selected. Table 2 shows some descriptive statistics of wind speed data in each of the seven stations including Latitude (Lat.), Longitude (Long.), data period, time interval, total recorded data, mean wind speed, standard deviation (Sd), maximum wind speed (Max.), locations and the data specifications for each station. According to Table 2, Chabahar (S7 station) has the highest mean wind speed with a value of 4.97 m/s, and therefore it has a great potential for harnessing wind energy.

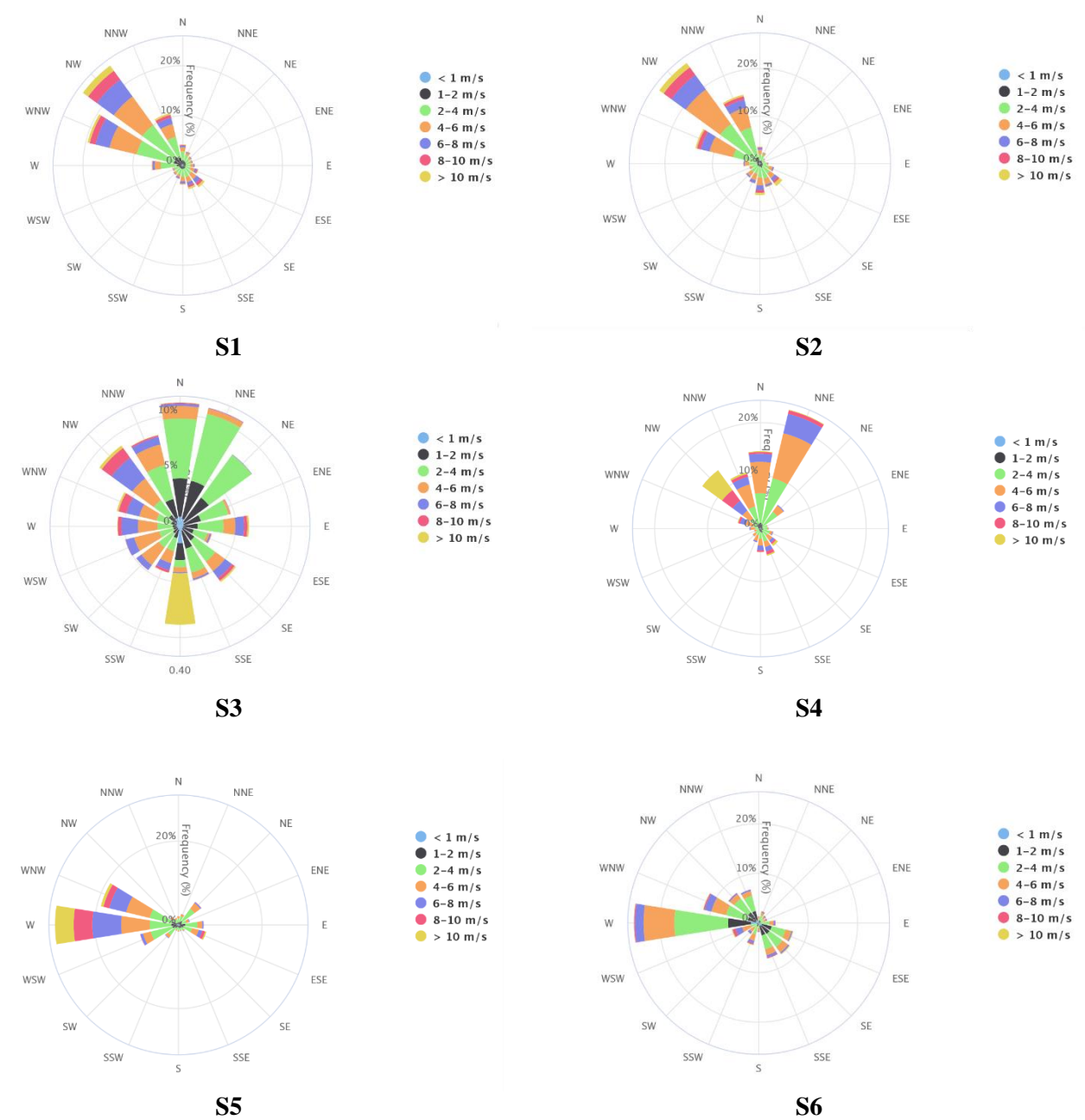
Table 2 Location and properties of studied wind data [42]

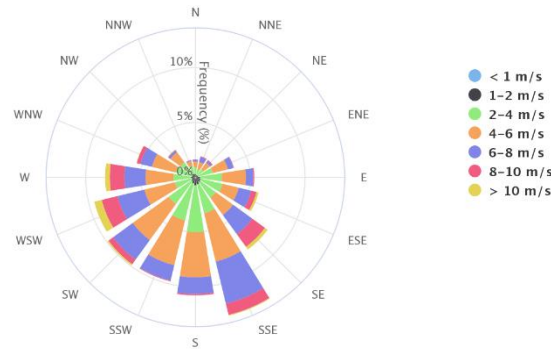
Station	Designate	Lat. (N)	Long. (E)	Data period	Time interval	Total recorded Data	Data Statistics		
							Mean	Sd	Max.
Abadan	S1	30.447	48.306	2007-2009	10-min	90656	4.35	2.51	19.76
Mahshahr	S2	30.579	49.086	2007-2009	10-min	91923	4.44	2.41	21.46
Delvar	S3	28.835	51.046	2006-2008	10-min	72186	3.40	2.14	15.92
Bordekhoon	S4	27.985	51.492	2006-2008	10-min	82492	4.87	2.73	19.93
Kish	S5	26.553	53.910	2006-2008	10-min	81217	4.59	2.81	22.38
Jask	S6	25.685	58.109	2006-2007	10-min	59518	3.44	2.04	20.82
Chabahar	S7	25.328	60.663	2008-2009	10-min	73296	4.97	2.14	15.41



Figure 2 Location of seven stations across the southern coasts of Iran, under study

One of the most effective factors in wind energy studies is wind direction distribution. Wind direction determines the optimal position of wind turbines and the whole array of wind farms. A wind rose is the best indicator for the wind direction distribution. This graphical representative plays a vital role in choosing turbines and their alignments in the wind farm. Figure 3 shows wind roses of seven selected stations. As seen in these figures, dominant wind directions for stations S1 to S7 are NW, NW, N, NNE, W, W and SSE, respectively.





S7

**Figure 3** Wind rose diagrams for stations (Wind roses plotted using SATBA data in highcharts.com [42])

### 3. Analysis

A plausible resource assessment must be able to identify appropriate locations with strong, moderate, and weak winds. In the past, the assessment was performed through “wind deformed conifer trees”. Here, trees and vegetation were the natural indicators for both wind speed and direction. By observing the local place for long times, a rough idea about the wind richness of the place could be achieved [43]. Various techniques are used to show the effect of wind on trees in terms of numbers such as the Griggs-Putnam index [44]. A comprehensive review of these techniques was performed by Murthy et al. [1].

Although natural indicators are inexpensive, ubiquitous, simple, and conceivable to identify eligible locations, more detailed measurements must be performed to achieve better insight into station characteristics. With the advent of new technologies to measure wind properties, new horizons were broadened for the energy industry. To establish a meaningful analysis, a statistical analysis must be conducted. This procedure demands a time series record of wind speeds. Originally, measurement devices were used for airports across the world. Besides, there are other technologies for on-station measurements. Therefore, the wind characteristics data pave the way for more precious and detailed researches in the energy industry.

Wind energy is the kinetic energy of air in motion. Total wind energy through an assumed surface area could be calculated through Eq. (1):

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avtp)v^2 = \frac{1}{2}At\rho v^3 \quad (1)$$

$\rho$  is the air density,  $v$  is the wind speed and  $Avt$  combination is equal to the volume of air passing through the surface at the given time. Air density could be analyzed through statistical distributions to gain more concrete results [45]. In this study, air density is assumed to be constant. So, the term  $Avtp$  is equal to the mass of air flowing through assumed surface area (e.g. Rotor swept area of wind turbine). Power is energy per time unit; therefore, the output power of wind is [46]:

$$P = \frac{E}{t} = \frac{1}{2}A\rho v^3 \quad (2)$$

Figure 4 shows the flowchart of this study. The initial step for any wind power feasibility study is the technical assessment. The vital part of the technical assessment is to study and analyze the statistical characteristics of wind speeds because the energy output of the field considerably depends on wind speeds and their patterns. Various studies asserted that the main part of the assessment is finding the Probability Density Function (PDF) through wind speeds data as the main input into wind turbine design, station planning and operational plan [47]. After finding a suitable distribution, the wind energy potential can be determined. The next step is to calculate the wind turbine capacity factor for all available options. If the capacity factor is less than 0.25, the selected turbine model is rejected. Else, it is selected as a potential option and annual energy output is calculated for it [48].



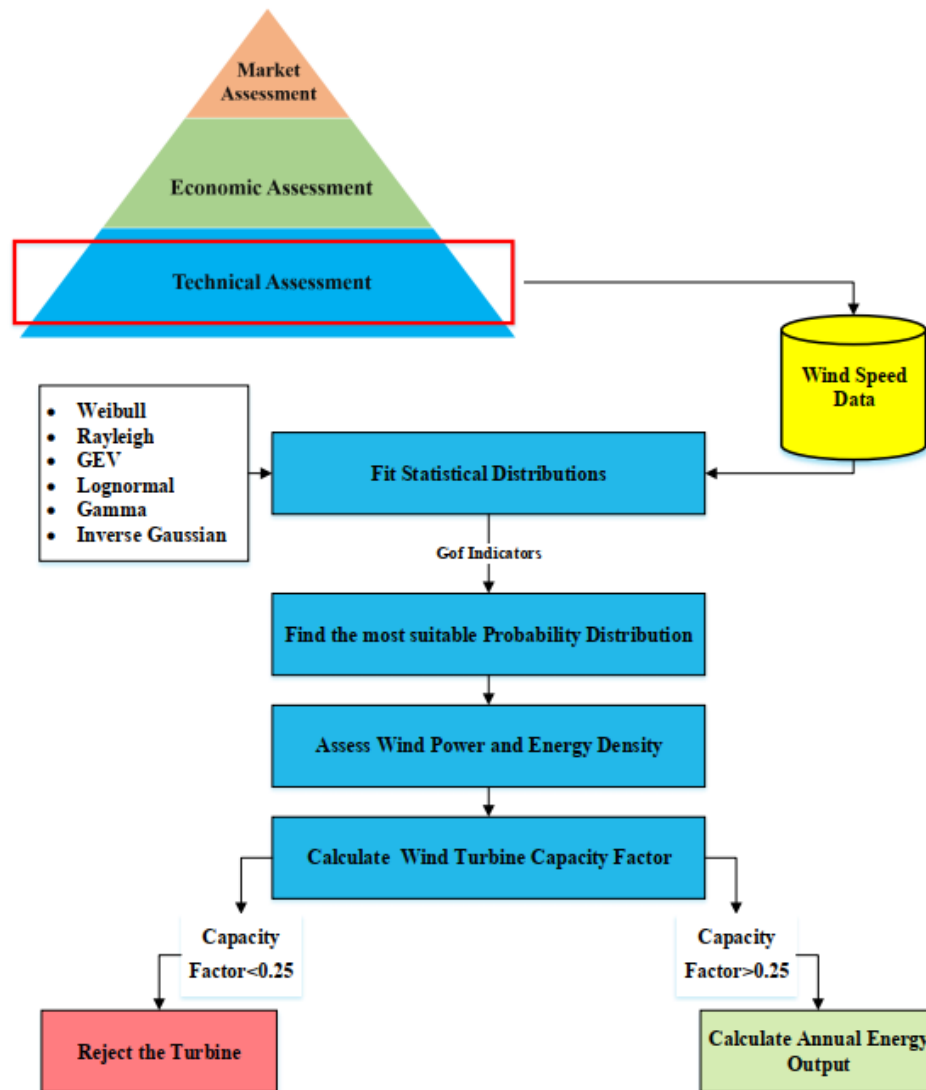


Figure 4 Outline of the method used in this study

### 3.1. Wind speed distribution models

In statistics, a unimodal distribution function refers to a continuous probability distribution that contains a single clear peak or the most frequent value. A diverse range of unimodal distribution functions was used in previous studies for modeling the PDF of wind speed including Weibull function, Gamma function, Rayleigh function, logistic function, Log-normal function, etc. Equations of these PDFs are listed in Table 3. Sometimes, wind speed data do not have a single clear peak. In these cases, multimodal probability distributions may provide a better fit to the data. Among these functions, the Weibull function is most used because of its simplicity and flexible parameters [23,37,49–53] (also see **Error! Reference source not found.**). Although the Weibull is capable of analyzing very low wind speeds close to 0 m/s, it cannot represent the wind structure nature thoroughly [54–56]. One of the main limitations of the Weibull function is that it cannot accurately capture the effect of calm winds. A solution for this issue is to use some mixture functions like two-component mixture Weibull function (Weibull-Weibull) or truncated normal Weibull mixture (Normal-Weibull). This approach has been comprehensively studied by Tian et al. [57].

**Table 3 Investigated PDFs and their parameters**

Name	Probability Distribution Functions	Parameters
<b>Weibull</b> [58]	$f(v) = \frac{k}{c} \cdot \left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^k}$	k: shape c: scale
<b>Rayleigh</b> [33]	$f(v) = \frac{2v}{c^2} \cdot e^{-\left(\frac{v}{c}\right)^2}$	c: scale
<b>Lognormal</b> [22]	$f(v) = \frac{1}{c \cdot v \cdot \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\ln(v) - k}{c} \right)^2 \right]$	k: shape c: scale
<b>Gamma</b> [59]	$f(v) = \frac{v^{k-1}}{\Gamma(k) \cdot c^k} \exp \left( -\frac{v}{c} \right)$	k: shape c: scale
<b>Inverse Gaussian</b> [17]	$f(v) = \left( \frac{k}{2\pi v^3} \right)^{\frac{1}{2}} \cdot \exp \left[ -\frac{k(v-c)^2}{2vc^2} \right]$	k: shape c: scale
<b>Generalized Extreme Value</b> [60]	$f(v) = \frac{1}{\sigma} \left( 1 + k \frac{v-\mu}{\sigma} \right)^{-1-\frac{1}{k}} \exp \left[ -\left( 1 + k \frac{v-\mu}{\sigma} \right)^{-\frac{1}{k}} \right]$	k: shape $\sigma$ : scale $\mu$ : location

In more complex and accurate studies, air density could be related to the height from the ground or sea surface and model the relation between them for calculating Eq. (2). Therefore, there must be two variations for estimating power output, wind speed, and air density. A Bivariate Probability Model (BPM) was proposed by Carta et al. to model the wind speed and air density interactions in Spain [61].

As stated before, Weibull distribution is the most used PDF for sake of statistical analysis of wind speed data (see **Error! Reference source not found.**). The first and prior stage to use Weibull distribution for investigating wind speed patterns, is to compute its distribution parameters. There are several methods in scientific contexts about this subject. Some of them are:

- Graphical method or Least squares algorithm [62]
- Maximum likelihood method (MLE) [50]
- Modified maximum likelihood method (MMLE) [50,63]
- Moments Method (MM) [50]
- Standard deviation method (Rocha et al. 2012)
- Empirical method of Jestus [64]
- Empirical method of Lysen [65]
- Equivalent energy method [63]
- Energy pattern factor method (power density method) [66]
- WAsP method [1]

Three of the above-mentioned methods were most used in various studies: maximum likelihood [67–73], empirical method [21,48,52,74,75], and graphical method [76,77]. Besides, method of moments [78–80], energy pattern factor [50], equivalent energy method, and WAsP[50] are the other methods used for calculation of Weibull coefficients. Different studies have compared the effectiveness of these methods. As mentioned in Shoaib et al. study, using energy pattern factor method, maximum likelihood, and modified maximum likelihood, results stated that maximum likelihood method is the most reliable method [81]. In one of the most comprehensive studies among different algorithms for determining Weibull coefficients, Rocha et al. attempts to evaluate and compare graphical, empirical, moment, Energy pattern factor, maximum likelihood, modified maximum likelihood, and equivalent energy methods in Brazil. It has been observed that equivalent energy method is the best method to calculate coefficients and graphical and energy pattern factor methods are the least effective ones to find coefficient values [82]. Solyali et al., used WAsP (Wind Atlas Analysis and Application), maximum likelihood, and graphical method algorithms [83]. Results indicate that WAsP algorithm gains the highest correlation with the actual data. Allouhi et al., chose maximum likelihood, graphical, and WAsP methods to compute coefficients in Morocco [63]. Maximum likelihood presents the best fit with the actual data. Masseran, comprehensively compared Weibull, Rayleigh, Lognormal, Burr, Exponential, Inverse Gaussian, and Inverse Gamma in two stations in Malaysia [84]. Surprisingly,

Gamma function shown the best accuracy for the two stations, based on combination of four goodness of fit indicator.

3.1.1 Wind speed extrapolation

Data record used in this study represents the wind specifications at the height of 10m above ground. To find wind speed at the height of turbine hub, power law has been used to convert the wind speed. The wind speed fluctuations near ground surface are referred to as wind shear. In the atmospheric surface boundary layer in which height does not exceed 150m above ground surface, power law rule is a reliable tool to extrapolate wind speeds at different heights [85]. It can be expressed by Eq. (3):

$$\frac{V_H}{V_R} = \left(\frac{H}{R}\right)^\alpha \tag{3}$$

where  $V_H$  is the wind speed at height  $H$ , and  $V_R$  is the reference wind speed at the reference height  $R$  which is 10m in the wind speed data,  $\alpha$  coefficient is the Hellmann exponent, also named the wind shear coefficient (WSC). The WSC varies regarding ground level height, time of day, atmospheric stability, humidity, and roughness of terrain. The general values of WSCs are summarized in Table 4 [86]. In this study, the WSC coefficient is assumed to be equal to 0.2 due to a lack of reliable data for the stations.

Table 4 Wind Shear Coefficient (WSC) [86]

Terrain type	WSC
Lake, ocean and smooth hard ground	0.10
Foot high grass on ground level	0.15
Tall crops, hedges, and shrubs	0.20
Wooded country	0.25
Small town with some trees and shrubs	0.30
City area with tall buildings	0.40

3.1.2. Goodness of Fit tests

Now it is time to assess the goodness of fitted PDFs for modeling the wind speed probability distribution. There are various Goodness-of-Fit (GoF) tests to assess the quality of fitted distributions. The coefficient of determination ( $R^2$ ) is used to measure the linear relationship between the observed and predicted probabilities. Also, root-mean-square error (RMSE) is utilized to show the level of concentration of data around the fitted distribution. Besides, because of using MLE method for parameter estimation Akaike information criterion (AIC) and Bayesian information criterion (BIC) are used to assess the accuracy of the fitted distribution. Table 5 presents the formulae and definitions of parameters for each of these four statistical indicators. Lower values for RMSE, AIC, and BIC indicate a higher goodness of fit, while on the contrary, a larger value for  $R^2$  shows better effectiveness of the fitted distribution.

Table 5 Goodness-of-Fit (GoF) tests in this study

Indicator	Formula	Parameters
$R^2$	$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - y_{ic})^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$	$y_i$ : Observed data $y_{ic}$ : fitted data $n$ : Number of data samples.
RMSE	$RMSE = \left[ \frac{1}{n} \sum_{i=1}^n (y_i - y_{ic})^2 \right]^{\frac{1}{2}}$	$y_i$ : Observed data $y_{ic}$ : fitted data $n$ : number of data samples
AIC	$AIC = -2 \log(L) + 2k$	L: likelihood $k$ : number of parameters
BIC	$BIC = -2 \log(L) + k \log n$	L: likelihood $k$ : number of parameters $n$ : number of data samples

### 3.2. Wind power and energy density

After calculating Weibull distribution function parameters, the next crucial step will determine wind power density through using Weibull distribution parameters. Wind power density is one of the most meaningful indicators to depict how powerful the winds are in a region within the defined time period. By contemplating the wind power density, quantification of the potential wind energy electricity is possible. Wind power is directly related to the area of turbine (i.e. swept area) and the cube of wind velocity at the station. Wind power can be calculated as Eq. (4):

$$P_w = \frac{1}{2} \rho A \int_0^{\infty} v^3 f(v) dv \quad (4)$$

Note that in the above equation, area of turbine and air density are considered as constant values. The more tangible indicator for wind energy is the power per unit area. It can be written as Eq. (5):

$$P_d = \int_0^{\infty} \frac{1}{2} \rho v^3 f(v) dv \quad (5)$$

The wind power density by using Weibull distribution for wind speed patterns will be stated as [48,63]:

$$P_d = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (6)$$

While using Rayleigh probability distribution function as a distribution of wind speeds, the wind power density function will be written as [87]:

$$P_d = \frac{3}{\pi} \rho c^3 \left(\frac{\pi}{4}\right)^{\frac{3}{2}} \quad (7)$$

For another distributions, there are not any analytic answers for the integral in Eq.(4). Therefore, the wind power density is calculated using numerical integration.

There is a reliable classification for every station based on National Renewable Energy Laboratory (NREL) to determine the relative wind power potential. This classification is based on observed and recorded wind speeds at the height of 50m. The wind power classification is given in Table 6 [88].

**Table 6 NREL wind power classifications**

Wind Power Class	Power Density (W/m <sup>2</sup> )	Description
1	0-200	Unsuitable for any wind applications
2	200-300	Suitable for Stand-alone
3	300-400	Good
4	400-500	Good
5	500-600	Excellent
6	600-800	Outstanding
7	800-2000	Superb

Wind energy density is the amount of energy produced for any arbitrary period of time. It can be written as Eq. (8):

$$P_d = \frac{E_d}{t} \quad (8)$$

### 3.3. Capacity Factor

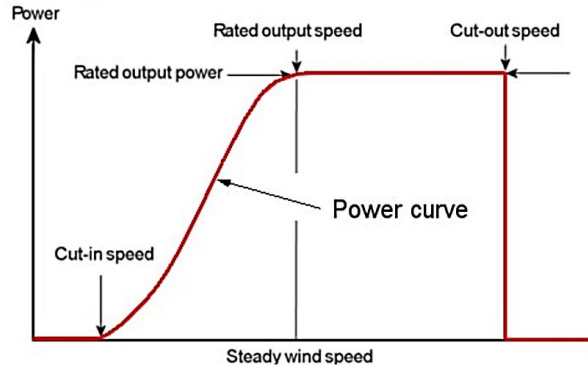
Capacity factor ( $C_f$ ) of a wind turbine is an indicator which defines the output viability of a wind turbine at a selected station. It determines the ratio of average power yield to the rated power of turbine.  $C_f$  is one the most reliable measures for choosing wind turbine because it inherently shows the performance of the wind turbine.  $C_f$  can be expressed as [48]:

$$C_f = \frac{P_{avg}}{P_r} = \frac{\text{Net annual energy production (MWh)}}{\text{Installed power (MW). Annual Hours}} \quad (9)$$

$P_r$  Represents the power output of wind turbine when the turbine runs as its rated power all the time in one year. Needless to say, the capacity factor is always less than 1. The  $P_{avg}$  can be expressed as [63]:

$$P_{avg} = \int_{v_{cut-in}}^{v_{cut-out}} P(v) \cdot f(v) dv \quad (10)$$

where  $f(v)$  is the probability distribution of wind speed and  $P(v)$  is the power curve of wind turbines. The cut-in wind speed is the minimum wind speed at which the turbine blades overcome the friction and begin to rotate. The cut-out wind speed is the speed at which turbine blades stopped rotating to prevent probable damages from high winds. It is notable that not all turbines have a well-defined cut-out speed. The schematic concept of power curve for a wind turbine is presented in Figure 5.



**Figure 5 Schematic power curve of a wind turbine [89]**

For pitch controlled turbines, the generated power from wind turbines can be estimated from the power curve as [48]:

$$P_{avg} = \begin{cases} P_r * c(v) & (v_{cut-in} \leq v_i \leq v_r) \\ P_r & (v_r \leq v_i \leq v_{cut-off}) \\ 0 & (v_i \leq v_{cut-in} \text{ or } v_i \geq v_{cut-off}) \end{cases} \quad (11)$$

The function  $c(v)$  denotes the wind turbine's output power in the interval between cut-in and cut-off speeds. In recent years, several studies have been conducted by scholars aiming to approximate this function [48,90–93]. The six most widely used functions for this purpose are listed as follows from Eq. (12) to Eq. (17):

$$c_1(v) = \frac{v - v_i}{v_r - v_i} \quad (12)$$

$$c_2(v) = \frac{(v - v_i)^2}{(v_r - v_i)^2} \quad (13)$$

$$c_3(v) = \frac{(v - v_i)^3}{(v_r - v_i)^3} \quad (14)$$

$$c_4(v) = \frac{v^2 - v_i^2}{v_r^2 - v_i^2} \quad (15)$$

$$c_5(v) = \frac{v^3 - v_i^3}{v_r^3 - v_i^3} \quad (16)$$

$$c_6(v) = \frac{v^3}{v_r^3} \quad (17)$$

Simultaneous power output of wind turbines in a wind farm is not the same because of spatial distribution of turbines and unpredictable and stochastic nature of wind speed distribution. Therefore, a more complicated approach is demanded to obtain the power output. Based on Wang et al., the average of above six functions is used for estimating the capacity factor [47].



$$C_f = \frac{P_{avg}}{P_r} = \left[ \int_{v_{cut-in}}^{v_r} c(v) f(v) dv + \int_{v_r}^{v_{cut-off}} f(v) dv \right] \quad (18)$$

So, the wind turbine will work within the speed period between cut-in and cut-off speeds.

### 3.4. Availability Factor

According to section 0, wind turbine will work within the wind speed interval between the cut-in and cut-off speeds. Thus, the availability factor of a wind turbine can be expressed as Eq. (19):

$$AF = \int_{v_{cut-in}}^{v_{cut-off}} f(v) dv \quad (19)$$

Where  $f(v)$  is the wind speed probability distribution function.

## 4. Results and discussion

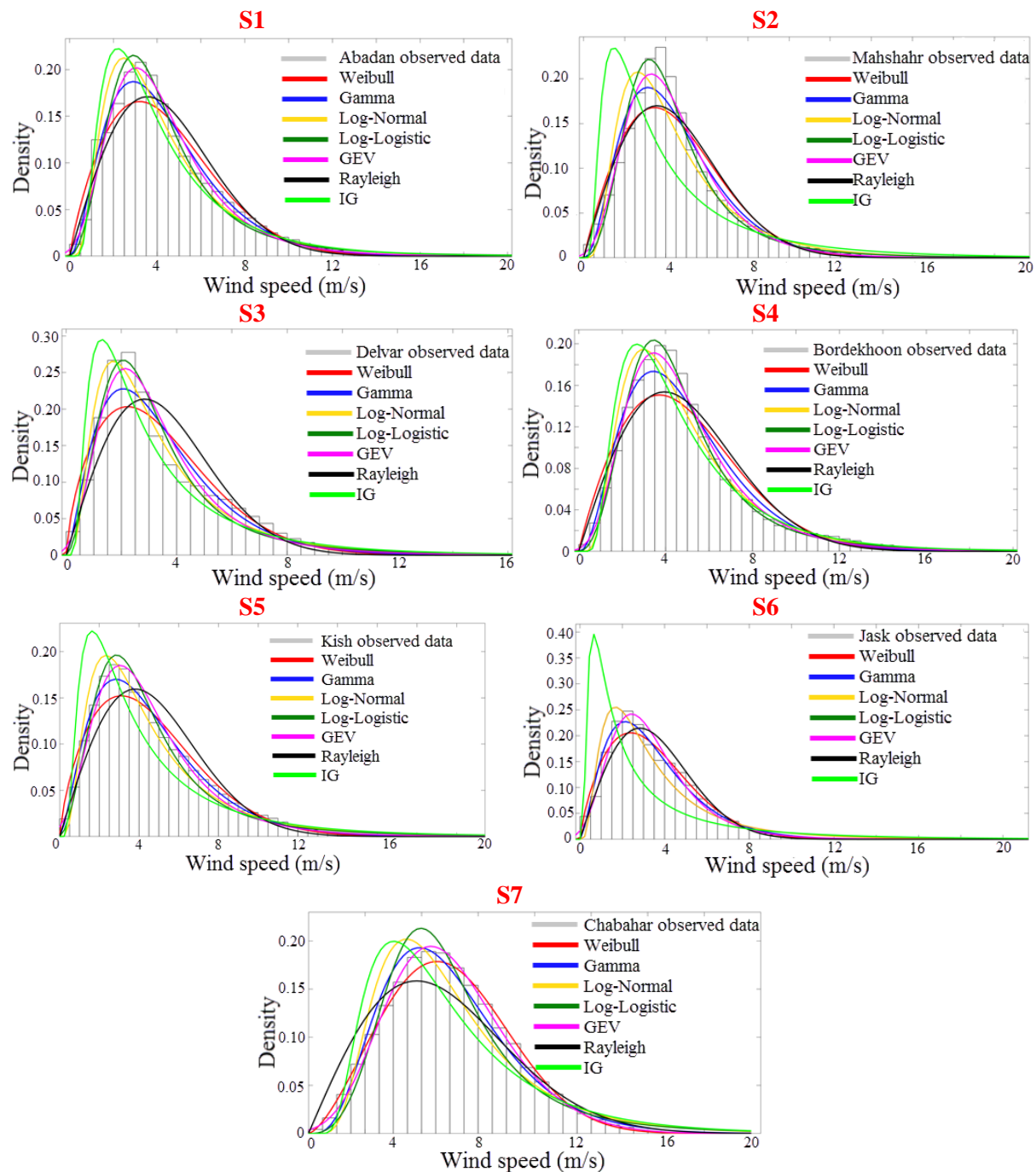
### 4.1. Analysis of distribution functions

Six different probability distributions, which are most widely used in the scientific literature, are fitted to wind speed data of each station. The Rayleigh PDF as a one-parameter function, Gamma, Log-normal, Weibull and Inverse Gaussian as two-parameter functions and finally, Generalized Extreme Value (GEV) as a three-parameter function are utilized for this purpose. MLE is used to estimate PDF parameters, since it is more efficient than other estimation methods, and generates a lower mean squared error [17]. The estimated parameters for each region are reported in Table 7. Note that the parameters are calculated from wind data at 10 meters above the ground.

**Table 7 Estimated parameters of probability distribution functions of the stations at height of 10 m**

Station	Distribution					
	Weibull	Gamma	Lognormal	GEV	Rayleigh	IG
<b>S1</b>	k=1.837, c=4.910	k=3.019, c=1.440	LL=1.295, LS=0.625	k=0.0702, sigma=1.825, mu=3.157	c=3.548	k=8.798, c=4.347
<b>S2</b>	k=1.942, c=5.012	k=3.390, c=1.309	LL=1.33541, LS=0.607406	k=0.032, sigma=1.791, mu= 3.345	c=3.569	k=4.919, c=4.438
<b>S3</b>	k=1.677, c=3.821	k=2.540, c=1.338	LL=1.014, LS=0.694	k=0.1432, sigma=1.454, mu=2.334	c=2.841	k=4.495, c=3.399
<b>S4</b>	k= 1.899, c=5.508	k=3.392, c=1.436	LL=1.428, LS=0.659	k=0.077, sigma=1.928, mu=3.597	c=3.946	k=11.435, c=4.869
<b>S5</b>	k=1.720, c=5.164	k=2.620, c=1.752	LL=1.321, LS=0.690	k=0.093, sigma=1.997, mu=3.232	c=3.805	k=5.579, c=4.589
<b>S6</b>	k=1.755, c=3.862	k=2.625, c=1.310	LL=1.032, LS=0.723	k= 0.042, sigma=1.522, mu=2.492	c=2.826	k=1.955, c=3.438
<b>S7</b>	k=2.474, c=5.605	k=4.780, c=1.040	LL=1.495, LS=0.503	k=-0.124, sigma=1.908, mu=4.075	c=3.827	k=14.317, c=4.971

The wind speed distribution diagrams (PDF plots) for seven selected stations are shown in Figure 6. The horizontal axis of these diagrams shows the range of wind speed and the vertical axis is the probability density. It varies from zero to the highest possible value for each curve. As seen in figures, all distributions are skewed to the right (i.e. positive Skewness), and therefore, mean of wind speeds is bigger than mode and median of data.



**Figure 6 Wind speed distributions for seven selected stations at the height of 10m**

Four different GoF indicators are calculated for these functions and the results are reported in Table 8. Note that lower RMSE, AIC and BIC shows a better fitness. On the other hand, higher  $R^2$  shows a better correlation between observed data and fitted distribution. Note that different GoF indicators can yield different results. For example, in S3 station, Gamma performs better in terms of  $R^2$ , whereas Lognormal performs better in terms of RMSE. This paper assigns  $R^2$  a greater weight for the assessment, and selects it as the first reference index. Results show that Gamma is the best distribution for S1, S3, S5, and GEV has the best fit for S2, S4, and S6. Weibull is only suitable for S7. Results show that  $R^2$  values for Weibull distribution are 1 to 7 % lower than that of for the best distribution in stations S1 to S6.

As seen above, one cannot use Weibull distribution for all stations without further investigations. Nevertheless, for engineering applications it is valuable to propose a so-called effective function which

has the best performance to be used for a specific geographical location. The results show that Gamma and GEV are the most effective function for the southern coasts of Iran since they have the best statistical performance. But, Gamma has two parameters, whereas GEV has three parameters. Therefore, Gamma is selected as the effective function for the southern coasts because of its more simplicity.

**Table 8 Comparison between six distribution functions in terms of four GoF indicators**

Station	Distribution Function	R <sup>2</sup>		RMSE		AIC		BIC	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank
S1	Weibull	0.953	4	0.045	4	404569	3	404551	3
	Gamma	0.989	1	0.026	1	401817	1	401798	1
	Lognormal	0.976	2	0.397	3	406898	5	406879	4
	GEV	0.972	3	0.345	2	402987	2	402959	2
	Rayleigh	0.943	5	0.049	5	405758	4	405766	5
	IG	0.921	6	0.058	6	412268	6	412276	6
S2	Weibull	0.924	3	0.061	4	406040	3	406059	3
	Gamma	0.959	2	0.045	2	403145	2	403164	2
	Lognormal	0.917	4	0.064	5	414720	5	414739	5
	GEV	0.988	1	0.029	1	400500	1	400528	1
	Rayleigh	0.924	3	0.059	3	406188	4	406196	4
	IG	0.516	5	0.15	6	406188	4	406196	4
S3	Weibull	0.913	4	0.068	3	295197	3	295215	3
	Gamma	0.969	1	0.049	2	293315	1	293334	1
	Lognormal	0.955	2	0.041	1	298399	4	298418	4
	GEV	0.929	3	0.076	4	294194	2	294222	2
	Rayleigh	0.857	6	0.09	6	299472	5	299479	5
	IG	0.877	5	0.084	5	315908	6	315916	6
S4	Weibull	0.924	4	0.055	4	381906	5	381888	5
	Gamma	0.976	2	0.031	2	377063	2	377082	2
	Lognormal	0.963	3	0.039	3	380270	4	380289	4
	GEV	0.992	1	0.023	1	376076	1	376104	1
	Rayleigh	0.924	4	0.055	4	377578	3	377586	3
	IG	0.918	5	0.057	5	377578	3	377586	3
S5	Weibull	0.967	4	0.035	3	378525	3	378544	3
	Gamma	0.993	1	0.016	1	377071	1	377089	1
	Lognormal	0.974	2	0.032	2	384730	5	384748	5
	GEV	0.973	3	0.04	4	378108	2	378136	2
	Rayleigh	0.925	5	0.052	5	382014	4	382022	4
	IG	0.806	6	0.083	6	412722	6	412729	6
S6	Weibull	0.975	3	0.038	3	241574	2	241592	2
	Gamma	0.985	2	0.028	1	241851	3	241869	3
	Lognormal	0.937	5	0.06	5	253252	5	253270	5
	GEV	0.986	1	0.035	2	240873	1	240900	1

Station	Distribution Function	R <sup>2</sup>		RMSE		AIC		BIC	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank
	Rayleigh	0.958	4	0.048	4	243486	4	243493	4
	IG	0.246	6	0.205	6	313354	6	313361	6
S7	Weibull	0.994	1	0.015	1	315837	3	315856	2
	Gamma	0.984	4	0.024	4	317647	2	317666	3
	Lognormal	0.923	6	0.053	6	326363	5	32632	5
	GEV	0.969	5	0.033	5	315762	1	315789	1
	Rayleigh	0.99	3	0.021	3	320866	4	320874	4
	IG	0.991	2	0.02	2	341748	6	341756	6

To control the performance of the selected distributions, the results of the current study are compared against previous studies (if possible) in the same stations, based on the resulted R<sup>2</sup> values. In Mahshahr city (S2), GEV distribution gives better performance than Weibull function used in Nedaei et al. [15]. In Delvar (S3) and Bordekhon (S4) cities, Gamma and GEV distributions resulted more accurate output than Weibull distribution comparing with Dabbaghiyan et al. [94]. In Kish Island (S5), Gamma distribution shows a better fit in comparison with Nedaei and Mohammadi et al. who used Weibull distribution [26,31]. For Jask city (S6), GEV distribution revealed more reliable fitness than Weibull used in Nedaei study [26]. Eventually, in Chabahar city (S7), Weibull distribution is the most suitable distribution which is consistent with studies conducted by Alavi et al. [17], Nedaei [26], Mohammadi et al. [31], and Minaeian et al. [38] but the R<sup>2</sup> value is slightly higher in the current study.

## 4.2. Analysis of wind power and energy density

The wind power density for each station is determined using the best-fitted probability distribution at 10, 30, and 50 meters above the ground. Once the wind power density is calculated, wind energy density can be found. In this study, wind energy density is computed for one year. The results are gathered in Table 9. For sake of comparison, wind powers for each height across the stations are shown in Figure 7.

**Table 9** Estimated wind power density and wind energy density and classification of the stations for the wind power based on NREL

Station	PDF	WPD ( $W/m^2$ )			WED ( $\frac{kWh}{m^2}/year$ )			Class
		10m	30m	50m	10m	30m	50m	
S1	Gamma	111	215	292	972	1883	2562	2
S2	GEV	112	216	295	981	1892	2584	2
S3	Gamma	111	214	293	972	1875	2567	2
S4	GEV	161	311	423	1410	2724	3705	4
S5	Gamma	144	279	379	1261	2444	3319	3
S6	GEV	61	117	160	534	1025	1402	1
S7	Weibull	119	231	314	1042	2024	2751	3

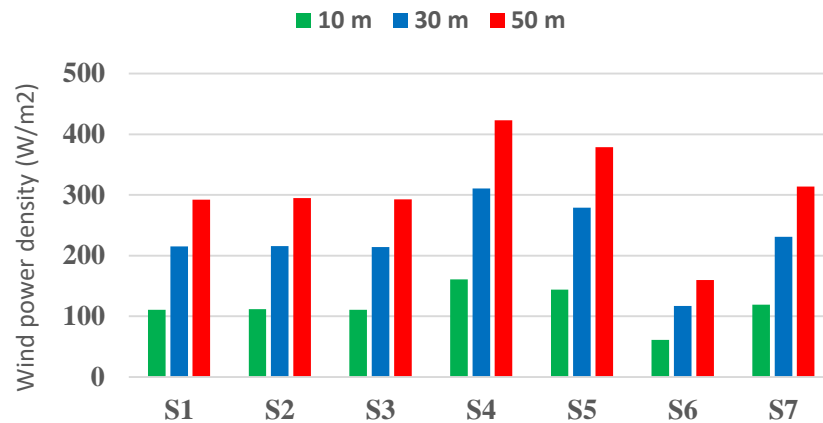


Figure 7 Wind power density for 7 stations at heights of 10, 30, and 50 m

### 4.3. Wind turbine selection

Fifteen wind turbines with hub heights ranging 20-100 meters and rated powers ranging 0.055-4.2 MW are exploited for assessing wind performance. This range of wind turbine power classes could be useful in the next steps of economic and feasibility analysis for establishing wind farm. Wind turbines characteristics are listed in Table 10.

Table 10 Characteristics of wind turbines used in the study [95]

Turbine Model	Name	Rated Power Output (MW)	Hub Height(m)	Cut-in wind Speed (m/s)	Rated wind speed (m/s)	Cut-out wind Speed (m/s)	Swept Area (m <sup>2</sup> )
Vestas V15	T1	0.055	20	4	12.5	25	176
AIRCON 10 S	T2	0.0098	30	3.5	11	25	39.6
Enercon E-12	T3	0.03	30	3	11	35	113
Enercon E-44	T4	0.9	45	3	16.5	34	1521
Enercon E-30	T5	0.3	50	2.5	13.5	25	707
Goldwind S43/600	T6	0.6	50	3	14	25	1452
Vestas V52	T7	0.85	55	4	14	25	2124
Goldwind S50/750	T8	0.75	60	3.5	14.5	25	1964
Nordex N54	T9	1	60	3.5	14	25	2290
Suzlon S.33-350	T10	0.35	70	3.5	14	25	876.1
United Power UP2000-97	T11	2	80	3	10.1	25	7390
Goldwind GW 62/1200	T12	1.2	85	3	12.5	25	3000
Envision EN106-1.8	T13	1.8	90	3	9.5	20	8825
General Electric GE 1.6 - 100	T14	1.6	100	3.5	11	25	7854
Senvion 4.2M118	T15	4.2	100	3	12.5	22	10936

To evaluate the energy output of each turbine, wind speed distribution parameters have been calculated at the hub-height. Consequently, wind turbine capacity factor and availability factor are determined using Eq. (18) and Eq. (19), respectively.

For cost-effective investment in wind energy sector, it is asserted that the capacity factor of wind turbine should be between 0.25-0.45 to be economically efficient and feasible [96]. According to Ayodele et al., any wind turbine with capacity factor lower than 0.25 will not be suitable to be integrated into the grid [48]. Estimated capacity factors for all wind turbines are listed in :



Table 11:

**Table 11 Estimated Capacity factor of wind turbines for each turbine across the seven stations**

<b>Turbine</b>	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>	<b>S7</b>
<b>T1</b>	0.120	0.117	0.080	0.151	0.146	0.065	0.145
<b>T2</b>	0.204	0.202	0.129	0.245	0.235	0.119	0.264
<b>T3</b>	0.217	0.216	0.139	0.260	0.247	0.130	0.279
<b>T4</b>	0.119	0.118	0.082	0.148	0.141	0.070	0.141
<b>T5</b>	0.194	0.194	0.127	0.232	0.222	0.120	0.242
<b>T6</b>	0.172	0.171	0.112	0.207	0.199	0.103	0.213
<b>T7</b>	0.161	0.158	0.103	0.195	0.189	0.092	0.201
<b>T8</b>	0.166	0.164	0.106	0.200	0.192	0.097	0.206
<b>T9</b>	0.177	0.175	0.113	0.213	0.205	0.104	0.222
<b>T10</b>	0.190	0.188	0.121	0.227	0.218	0.113	0.240
<b>T11</b>	0.360	0.367	0.226	0.416	0.388	0.237	0.481
<b>T12</b>	0.258	0.258	0.163	0.302	0.298	0.162	0.336
<b>T13</b>	0.401	0.412	0.248	0.455	0.421	0.273	0.540
<b>T14</b>	0.330	0.335	0.204	0.382	0.359	0.213	0.444
<b>T15</b>	0.278	0.279	0.172	0.320	0.304	0.178	0.368

Capacity factors higher than 0.25 could be plausible for a wind turbine[48]. Based on this, in Abadan, T11 to T15 are suitable for wind energy production. The table reveals that in Mahshahr again T11 to T15 are reliable for energy production. After that, in Delvar station, there is not any capacity factor higher than 0.25 but, T13 has the highest capacity factor. In Bordekhooon, one the most suitable stations, T3 and T11 to T15 are suitable choices. Kish, the most important island of the Persian Gulf for tourism, again T11 to T15 are good for wind energy production. Jask has not any acceptable capacity factors due to poor wind power density. Eventually, in Chabahar station, T2, T3, and T11 to T15 are acceptable wind turbines with significant capacity factors.

Availability factor for each wind turbine in each station has been calculated and shown in Table 12. As shown in Table 12, Bordekhooon and Chabahar stations have the greatest availability factors among stations. This fact could be realized from their greater wind power density and their higher average wind speed. After them, Kish, Mahshahr, and Abadan have the greatest availability factors. Jask and Delvar are the least in availability factors due their poor wind power density. Among wind turbines, T5 has the greatest average of availability factor because it has the least cut-in speed and this turbine cover the wider range of applicable wind speeds.

**Table 12 Estimated Availability factor of wind turbines for each turbine across the seven stations**

	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>	<b>S6</b>	<b>S7</b>
<b>T1</b>	0.570	0.604	0.366	0.653	0.585	0.410	0.735
<b>T2</b>	0.695	0.741	0.487	0.778	0.698	0.542	0.834
<b>T3</b>	0.733	0.816	0.577	0.847	0.766	0.630	0.884
<b>T4</b>	0.802	0.848	0.622	0.875	0.797	0.672	0.904
<b>T5</b>	0.809	0.907	0.724	0.924	0.860	0.765	0.941
<b>T6</b>	0.731	0.855	0.630	0.879	0.803	0.683	0.908
<b>T7</b>	0.687	0.733	0.478	0.771	0.691	0.535	0.830
<b>T8</b>	0.761	0.809	0.564	0.838	0.758	0.621	0.879
<b>T9</b>	0.761	0.801	0.564	0.838	0.758	0.638	0.879
<b>T10</b>	0.774	0.822	0.581	0.849	0.770	0.727	0.888

	S1	S2	S3	S4	S5	S6	S7
T11	0.842	0.884	0.678	0.903	0.833	0.726	0.926
T12	0.731	0.884	0.678	0.903	0.839	0.730	0.926
T13	0.844	0.884	0.682	0.897	0.829	0.736	0.930
T14	0.803	0.848	0.619	0.872	0.795	0.675	0.905
T15	0.731	0.893	0.696	0.906	0.840	0.746	0.934

Using the criteria in which the acceptable capacity factor must be higher than 0.25, the selected wind turbines and their annual energy output are calculated in Table 13.

**Table 13 Annual energy output (MWh) for selected turbines on the stations**

Station	Turbine	T2	T3	T11	T12	T13	T14	T15
S1	Capacity factor	-	-	0.360	0.258	0.401	0.330	0.278
	Annual energy output (MWh)	-	-	6312	2710	6315	4630	10223
S2	Capacity factor	-	-	0.367	0.258	0.412	0.335	0.279
	Annual energy output (MWh)	-	-	6432	2716	6489	4691	10273
S4	Capacity factor	-	0.260	0.416	0.302	0.455	0.382	0.320
	Annual energy output (MWh)	-	68	7282	3172	7168	5358	11783
S5	Capacity factor	-	-	0.388	0.298	0.421	0.359	0.304
	Annual energy output (MWh)	-	-	6796	3136	6631	5027	11170
S7	Capacity factor	0.264	0.279	0.481	0.336	0.540	0.444	0.368
	Annual energy output (MWh)	23	73	8423	3530	8517	6218	13538

#### 4.4. Comparison with previous studies

In Abadan (S1), there is one similar research for wind energy potential [25]. The data used in this study is the same with current research. Weibull distribution was deployed for characterizing wind speed patterns. Nevertheless, Weibull distribution ranked fourth among distributions used in this study. The best PDF for S1 is Gamma distribution. Precise comparison for goodness of fit is not possible because it was not reported in that paper.

For Mahshahr city (S2), Nedaei et al. studied data with 19 months duration for the region and used Weibull, Rayleigh, and Lognormal distributions [15]. Reported  $R^2$  in that paper are 0.923, 0.910, and 0.901, respectively, which are consistent with  $R^2$  of the current study with the values 0.926, 0.924, and 0.917. Furthermore, in the current study, GEV has the best performance in term of  $R^2$  value and has  $R^2 = 0.988$ .

In Delvar city (S3), Dabbaghiyan et al. studied wind speed data for 2011 [37]. They deployed Weibull distribution for wind speed, but  $R^2$  is not published. While, in this study, Gamma function is selected for this location with  $R^2 = 0.969$ .

Two researches have been conducted on Kish Island (S5). Nedaei studied wind data between 2006 and 2007 and also selected Weibull distribution [26].  $R^2$  for Weibull distribution was 0.986, while Gamma distribution has the highest  $R^2$  equal to 0.993 in the current study. Although  $R^2$  is slightly increased, different data sources should be considered. Another study in the region is performed by Mohammadi et al. [31] based on long-term data from 2002 to 2009. Again, Weibull distribution opted.

$R^2$  was not calculated. Wind power density at the height of 10m reported  $111 \text{ W/m}^2$ , while this research calculated  $144 \text{ W/m}^2$  using Gamma density function with  $R^2$  equal to 0.993.

In the Jask station (S6), Nedaei studied wind power density using data from 2006 to 2007 and Weibull distribution [26].  $R^2$  reported 0.9782 while in current research GEV function was the most suitable for the region with  $R^2 = 0.986$ . Weibull distribution ranked third among six PDFs with  $R^2 = 0.975$ , which is in line with the previous study.

Chabahar (S7) is the most studied location with three researches. Minaeian et al. studied wind speed data for 2007 and used Weibull distribution but  $R^2$  was not reported [38]. Mohammadi et al. studied data from 2002 to 2009 and used Weibull distribution [31]. Again,  $R^2$  was not announced. Wind power density at the height of 10m is calculated  $111 \text{ W/m}^2$  while in the current study, using Gamma function, wind power density is determined as  $119 \text{ W/m}^2$  which is slightly higher. This distinction might cause due to different wind speed data and distribution used. Moreover, Alavi et al. studied the station with data from 2008 to 2009. They conducted analysis using Weibull, Gamma, Lognormal, and GEV functions with  $R^2 = 0.999, 0.999, 0.998$ , and  $0.999$  respectively which are significantly high. Also, Nakagami distribution function yielded the best fitness with  $R^2 = 0.9999$ . Accordingly, in current study,  $R^2$  for those distributions are 0.994, 0.984, 0.923, and 0.969, respectively. Apart from Nakagami distribution, Weibull shows the best fitness in both studies and  $R^2$  of two analysis are approximately equal. The negligible difference might occur because of different data.

As mentioned above, current research enhanced goodness of fit for wind speed data according to  $R^2$  comparison with previous studies. Moreover, in other sections of analysis, a more precise approach is conducted to compute capacity factors. Also, to increase practicality of the article, a broad range of wind turbines are considered to analysis to obtain a more concrete insight toward wind energy capacity in south coastal zone of Iran.

## 5. Conclusion

This paper presented a comprehensive and step-by-step methodology for the wind energy assessment along with a case study in seven different stations covering the southern coastal borders of Iran. Besides, a comprehensive literature review is conducted to gain insight into the concept of wind energy assessment and efforts made in this field, their methodologies, and locations. Almost all previous studies in Iran utilized the Weibull function to estimate wind speed patterns in the selected area (see **Error! Reference source not found.**). Here, six different probability distribution functions ranging 1-3 parameters were exploited in order to find the best fitness to the wind speed data. Additionally, they exploited only a single function for determining the capacity factor of wind turbines. This study has shown that although the Weibull PDF is the most widely used function as wind speed distribution, in the area of interest, Gamma, GEV, and lognormal functions have better correlations with observed data. The second major finding was that based on distribution ranks, Gamma function is the most suitable distribution at the initial step of wind power assessment in the southern coasts of Iran. Also, the annual wind power density and energy output are determined for three heights above the ground surface. Based on power densities, Bordekhoon, Kish, and Chabahar are more suitable for harnessing wind energy. Jask has the least power density and Abadan, Mahshahr, and Delvar are suitable for stand-alone wind power facilities. Moreover, the capacity factor of wind turbines is calculated through six different functions and the average of these six functions is used as a final capacity factor value to have more reliable results. This provides an accurate evaluation of wind energy capacity. To analyze practical aspects of current study, fifteen wind turbines with hub heights ranging 20-100 meters and rated powers ranging 0.055-4.2 MW are exploited for assessing wind performance. Results show that as capacity factor increases with a hub height of wind turbine, T11 to T15 are the best wind turbines due to their capacity factors. The present study is the first (and also one of the few researches worldwide) comprehensive practical assessment of wind energy along with assessing different actual turbine models. Further research should be undertaken to explore socio-economic aspects of implementing wind energy farms in the southern coasts of Iran.

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