New Software for Matching Between Wind Sites and Wind Turbines

Ali M. Eltamaly

Abstract Wind energy system is becoming a mature technology for generating electric energy from the wind. The design of the wind energy system should take into consideration the matching between the wind speed site characteristics and the performance characteristics of the wind turbine. This chapter is introduced to perform the matching process between the site and the wind turbines (WTs) for minimum cost and highest reliability. An accurate matching methodology for pairing between site and WTs has been introduced. The pairing methodology is designed in Matlab code to perform this study. The input data for 32 Saudi Arabia sites and 140 market available WTs have been selected to validate the right operation of the new proposed computer program. This program will select the best site and the most suitable WT for this site based on techno-economical methodology. This program can help researchers, designers, experts, and decision-makers to select the best site among many sites and the best WT for each site. The results obtained from this site show a substantial reduction in cost when the best site is selected as the most suitable WT for this site.

1 Introduction

Wind turbines (WTs) have different technologies and different performance characteristics. At the same time, wind speed characteristics of sites are different from one site to another. Where one WT can generate high energy in some sites, meanwhile it may generate lower energy in some other sites because of the correlation between the wind turbine performance parameters and site parameters. To get the minimum cost of energy the suitable WT should be selected for minimum cost. This operation is called a pairing between the site and the WT. Based on this speed the suitable WT

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is operating at high efficiency in this site which can generate higher energy in this site which can be translated to a substantial reduction in the cost of energy. The most important parameters that characterize the operation of the WTs are the cut-in, rated, and furling wind speeds which highly affect the performance of the wind energy systems. The parameters of wind speeds sites that can characterize the wind speed profile of this site are the Weibull scale, *c* and shape, *k* parameters, and average wind speed. These two parameters can describe the wind speed profile better than many other statistical models such as gamma and Rayleigh models [1–12].

One of the simplest methodologies used to pair between sites and WT is done by estimating the average power output from the WT by using it in a certain site. Reference [1] performs direct numerical integrations for the output power corresponding to each wind speed to determine the average output power from WT. Despite the simplicity of this method, it needs a computer program to perform numerical integration [1]. On the other hand, reference [4] introduced some modifications to the previous method [1] by introducing formula to determine the average output power as a function of WT and site parameters.

Reference [4] proposes a technique to choose the best option from some of WT and sites. The wind speed data of wind sites and the data for WTs will be used to predict the capacity factors for each combination and the maximum value of capacity factor will be selected as the best option, and the site and WT were selected.

The Weibull parameters have been used for determining the wind profile for 32 sites in many countries around the world from data collected for several years. Also, the specifications of 20 different WT types were collected. The Weibull distributions of all 32 sites can be categorized into four types, type A to Type D. These sites are put in order from the lowest to highest average wind speeds where type A represents the sites with the lowest wind speed and Type D represents the highest one. The capacity factor, C_F is calculated for each WT–site pair, type A sites have very bad C_F indices because they do not have enough wind speed to reach the threshold of cut-in speeds. And type D has the highest capacity factor. It is concluded from this study that the WT has high cut-in wind speed and the high-rated wind speed will have a lower capacity factor and it represents an unsuitable candidate to be used in lower wind speed sites [4]. This methodology gets the final results based on the technical constraints and neglects the economic constraints. Due to the variation of the price for each kW of different WT types, the decision may not give us the best price for generated kWh. On the other hand, the yearly generated energy, and the cost of kWh produced were not estimated in these references [4, 5] and so this reduces the reliance upon in the assessment process.

Another study uses the Geographic Information System (GIS) to determine an analytic framework to evaluate site suitability for WTs depending on its wind speed and to select the best site based on an economical point of view. This methodology uses rule-based spatial analysis to determine suitable sites for WT placement. The selection strategy includes the wind energy components such as wind resources, and site obstacles, and terrain and some other environmental factors and human impact factors. The highest consideration is provided for the physical factors such as the placement of central loads to choose the best placement of the wind turbines taking the other factors such as the environmental and human impact factors in less consideration. The location of the intended wind energy project has been shown based on each separate factor and also based on the combination of more than one factor together [5]. This technique chooses sites depending on the highest average wind speed and overlooking the WT performance parameters which are the main drawback of this technique [5]. This technique [5] omitted assessment in economic terms, as in the previous methodologies [1, 4].

The capacity factor is used in many studies to pair between the site and the WT which is introduced in [4, 5]. The main drawback of this study is its building the pairing decision based on technical factors without giving the cost analysis any weight which is not enough to take this decision where the assessment steps should be based on the technical and economic factors. Taking the technical and economic factors are introduced in many studies in many sites in Saudi Arabia and Egypt [9, 13–15]. Another strategy used the value of money method to determine the present value of costs, *PVC*, of generated energy for the complete year. The *PVC* is used to estimate the cost generated energy by dividing the *PVC* by the total generated energy produced through the whole lifetime of the project [9, 13–15]. Another study used the monthly average wind speed of seven measurement stations located at the east coast of Egypt and two WT for pairing sites and WT [9].

The rest sections of this chapter are showing the models of WT in Sect. 2. The detailed discretion of the proposed computer program is introduced in Sect. 3. The results extracted from the 32 sites and the 140 WTs under study are introduced in Sect. 4. The last section is showing the conclusions extracted from the new proposed computer program.

2 Modeling of Wind Energy System

The mechanical energy extracted from wind is done by extracting the kinetic energy from moving winds. The wind power in the wind turbine depends on the wind speed, the cross-sectional area of the wind stream, and density of air at the site as shown in (1). It is clear from this equation that the power is directly proportional to the power three of the wind speed which means that the wind power is considerably affected by the wind speed. The height of the WT has a great effect on the wind speed and the generated energy from the WT. Most metrological stations are located at a level called the measurement height, h_g. Most of the wind speed measurement stations are located at 10 m above the ground level. The relationship governing the wind speed at any height, h is shown in Eq. (2) [2]. The WT cannot extract the whole generated power in the wind. The highest theoretical value that can be extracted from wind is 16/27 (0.593) which is called the Betz coefficient. Moreover, the wind turbine cannot start spinning at very low wind speed due to the friction and inertia weight of rotating components. Instead, it can spin and start to produce power at a certain wind speed called cut-in. At this speed, the WT can start to produce electric power. The cut-in wind speed differs from WT to another where its value is between 2.5 and

3.5 in most WTs. The good WTs have low cut-in wind speeds. The WT generates more power when the wind speeds exceed the cut-in wind speed until the wind speed reaches the rated wind speed of WT, u_r. Beyond the rated wind speed, the power will hold constant when the wind speed exceeds the rated wind speed to protect the components of wind turbines from overloaded conditions. The relationship between the generated power from WT against wind speed is different from one WT to another, but most of the WT has the relation as shown in Eq. (3). The generated power should stop once the wind speed reaches a certain high wind speed called cut-out or furling wind speed, u_f to protect the WT from damage due to very high wind speeds. The relation between the power in the wind and generated power from WT against wind speed is shown in Fig. 1. This relation shows the importance of wind speed on the generated power from WTs. So, it is recommended to choose sites with high average wind speed to extract more power. Also, it is recommended to choose WT with rated wind speed parameters suitable for this site. Based on the importance of wind speed on the generated power from WTs, many studies were introduced in the literature to select the best possible site from many sites [10, 14–51] which are very important before start installation of the wind energy projects. The generated power from WT is shown in (1).

$$P_w = \frac{1}{2}\rho A_t u^3 \quad (1)$$

where ρ is the air density.

A_t is the cross-sectional area of wind parcel, m

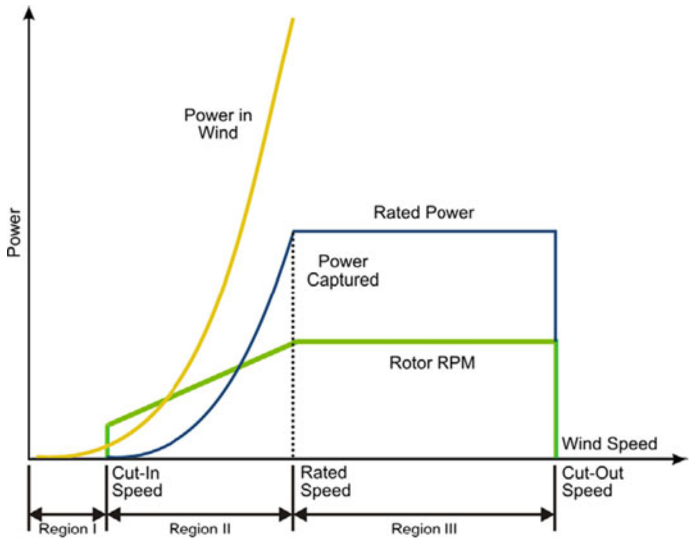


Fig. 1 Actual WT output power with the wind speed

u is the wind speed m/s

$$u(h) = u(hg) * \left(\frac{h}{hg}\right)^{\alpha} \tag{2}$$

where h: The height that the wind speed is needed to be determined above the ground level, m.

hg: The height of measuring the wind speed, m.

α: The power-law exponent, which depends on the roughness of the ground surface, its average value, is (1/7) [2].

$$P_W(u) = \begin{Bmatrix} 0 & u \le u_C \\ P_r * \frac{u-u_C}{u_r-u_C}, & u_C \le u \le u_r \\ P_r & u \ge u_r \\ 0 & u \ge u_f \end{Bmatrix} \tag{3}$$

The above equation is used to determine the generated power from the WT based on the wind speed parameters of the WT.

The wind speed is changing all the time, and for this reason, it should be modeled using statistical techniques. Weibull distribution is one of the most famous techniques used to model the speed of the wind as shown in the following equations;

The average wind speed u_{av} of measured wind speeds, u_i is shown in Eq. (4)

$$u_{av} = \frac{1}{n}\sum_{i=1}^{n} u_i \tag{4}$$

The Weibull density function, $f(u)$ that can represent the wind speed variation is shown in (5) where this function represents the frequency of speeds in the measurement data. This function has two parameters called the scale parameter, c (m/s), and shape parameter, k. The shape of distributed function for different values of shape factor, k at scale factor $c = 1$ is shown in Fig. 2. It is clear from this figure that the function is getting narrow as the shape factor is getting high value and vice versa.

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left(-\left(\frac{u}{c}\right)^{k}\right), \quad (k > 0,\ u > 0,\ c > 1) \tag{5}$$

There are many ways to determine c and k parameters as shown in the following equations. The empirical relationship between c and u_r as shown in Eq. (6) can give a good estimate when the shape factor is between 1.5 and 3 [2].

$$c = 1.12\,\overline{u} \qquad (1.5 \le k \le 3.0) \tag{6}$$

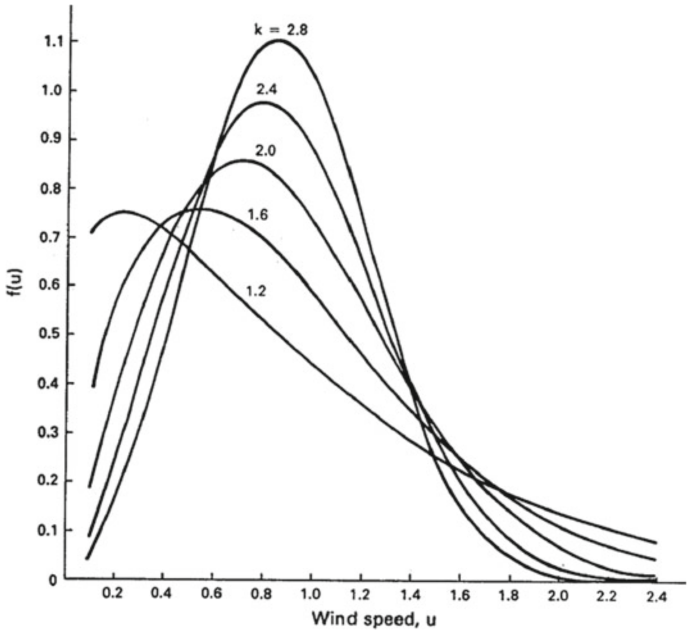


Fig. 2 The density function $f(u)$ along with the wind speed for different values of shape parameters at $c = 1$ [2]

Similar relation (7) can be used to estimate the shape parameter, k against the average wind speed, and variance of wind speeds [2].

$$k = \left(\frac{\sigma}{\overline{u}}\right)^{-1.086} \tag{7}$$

The standard deviation can be determined from (8) and the variance can be determined from this equation by taking the root of standard deviation.

$$\sigma^2 = c^2\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right] = (u)^2\left[\frac{\Gamma(1 + 2/k)}{\Gamma^2(1 + 1/k)} - 1\right] \tag{8}$$

Another Eq. (9) can be used to determine the relation between average wind speed and scale and shape parameters which can give an accurate estimation for these parameters in the range of shape parameters between 1 and 10 ($1 \leq k \leq 10$).

$$c = \frac{u}{\Gamma(1 + 1/k)} \tag{9}$$

Another statistical technique can be used to determine the scale and shape parameters as shown in (10) [52, 53].

$$k = a$$
$$c = \exp(-b/k) \tag{10}$$

where:

$$a = \frac{\sum_{i=1}^{w} x_i\, y_i - \frac{\sum_{i=1}^{w} x_i \sum_{i=1}^{w} y_i}{w}}{\sum_{i=1}^{w} x_i^2 - \frac{\left(\sum_{i=1}^{w} x_i\right)^2}{w}} = \frac{\sum_{i=1}^{w} (x_i - \overline{x}) \sum_{i=1}^{w} (y_i - \overline{y})}{\sum_{i=1}^{w} (x_i - \overline{x})^2} \tag{11}$$

$$b = \overline{y}_i - a\overline{x}_i = \frac{1}{w}\sum_{i=1}^{w} y_i - \frac{a}{w}\sum_{i=1}^{w} x_i \tag{12}$$

$$\text{And} \quad y_i = \ln(-\ln(1 - F(u_i))),$$
$$x_i = \ln(u_i) \tag{13}$$

The value of the capacity factor, *CF* using the site and WT parameters is shown in (14).

$$C_F = \frac{\exp\left[-(u_C/c)^k\right] - \exp\left[-(u_r/c)^k\right]}{(u_r/c)^k - (u_C/c)^k} - \exp\left[-(u_F/c)^k\right] \tag{14}$$

$$P_{W,av} = C_F * P_r \tag{15}$$

The average number of WTs, ANWT is determined by dividing the average load value $P_{LW,av}$ by the average power generated from WT as shown in Eq. (16).

$$ANWT = \frac{P_{LW,av}}{P_{W,av}} \tag{16}$$

3 The Proposed Computer Program Implementation

The first step of building a wind energy system in any country is to select the windy sites with high average wind speed and near to the load centers. These sites should be subject to more studies to select the best one and the best WT that can produce the required load with the lowest cost. The WT should be paired with the sites because the WTs can work economically in one site but it may not be suitable for another site. For this reason, the sites and the WTs data should be collected to select the best site and the best WT suitable for this site for the minimum cost of energy. For this reason, 32 sites were collected in many places in Saudi Arabia and 140 market available WTs were also selected to be studied. The detailed performance data of 10 of the 140 WTs are shown in Table 1. An efficient computer program is designed to

Table 1 Sample of the WT data used in the computer program

ID	Manufacturer	Model	Offshore	Power	Diameter	Hub min height	Hub max height	Min wind speed	Nominal wind speed	Max wind speed	Gear box	Output voltage	Power control
No	Company Name	Model Number	Installation Place	kW	m	m,	m	m/s,	m/s,	m/s,		V	
1	Enercon	E33/330	No	330	33.4	37	50	3	13	34	no	400	Pitch
2	Enercon	E44/900	No	900	44	45	65	3	13	34	no	400	Pitch
3	Enercon	E48/800	No	800	48	50	76	3	13	34	no	400	Pitch
4	Enercon	E53/800	No	800	52.9	60	75	2	13	34	no	400	Pitch
5	Enercon	E70/2300	No	2300	71	57	98	2	15	34	no	400	Pitch
6	Enercon	E82/2000	No	2000	82	78	138	2	13	34	no	400	Pitch
7	Nordex	N90/2500	Yes	2500	90	70	80	3	13	25	yes	690	Pitch
8	Nordex	N90/2300	Yes	2300	90	80	105	3	13	25	yes	690	Pitch
9	GE Energy	4.0-110	Yes	4000	110	80	110	3	14	25	no	690	Pitch
10	Nordex	S77	No	1500	77	61.5	100	3.5	12.5	25	yes	690	Pitch

perform the matching steps of the sites and the WTs. Many useful results like the best site and best WT for this site and other sites and the cost of generated energy from all sites with different WTs can be extracted from this computer program. Due to the generic nature of this computer program, it can be used in any place of the world and it can help decision-makers to select the best option to install the wind energy system and to predict the benefits out of the installation of these projects. The new proposed computer program has more flexibility and more accurate results than the market available commercial design programs like the HOMER or the RetScreen. The block diagram showing the logic of this computer program is shown in Fig. 3. This computer program is having five subroutines having flowcharts showing their logic as shown in Figs. 4, 5, 6, 7 and 8. These subroutines are listed in the following points and they will be discussed in the following sections.

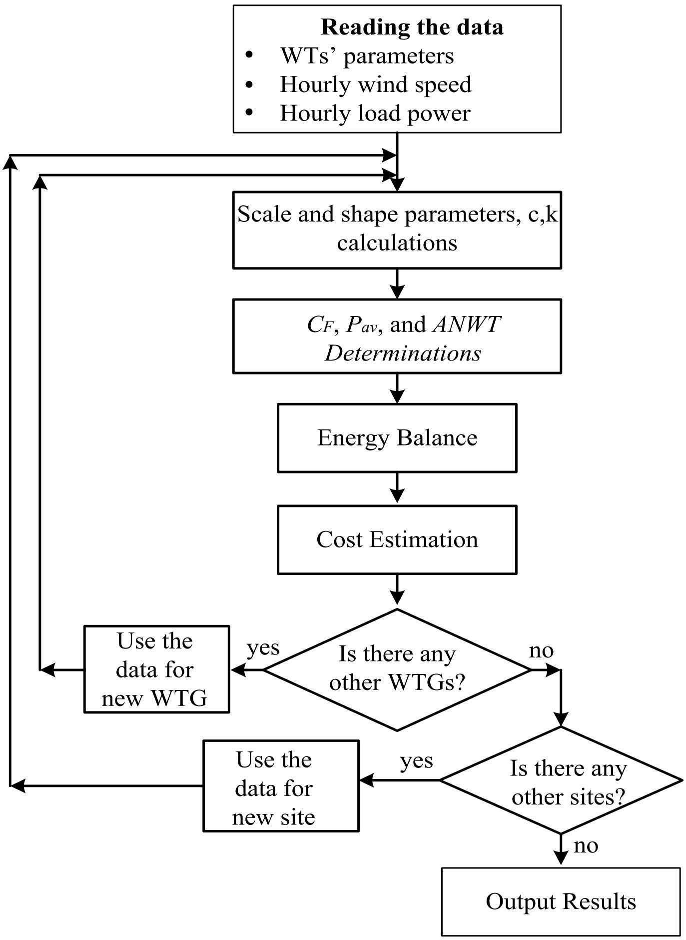


Fig. 3 The main logic of the computer program

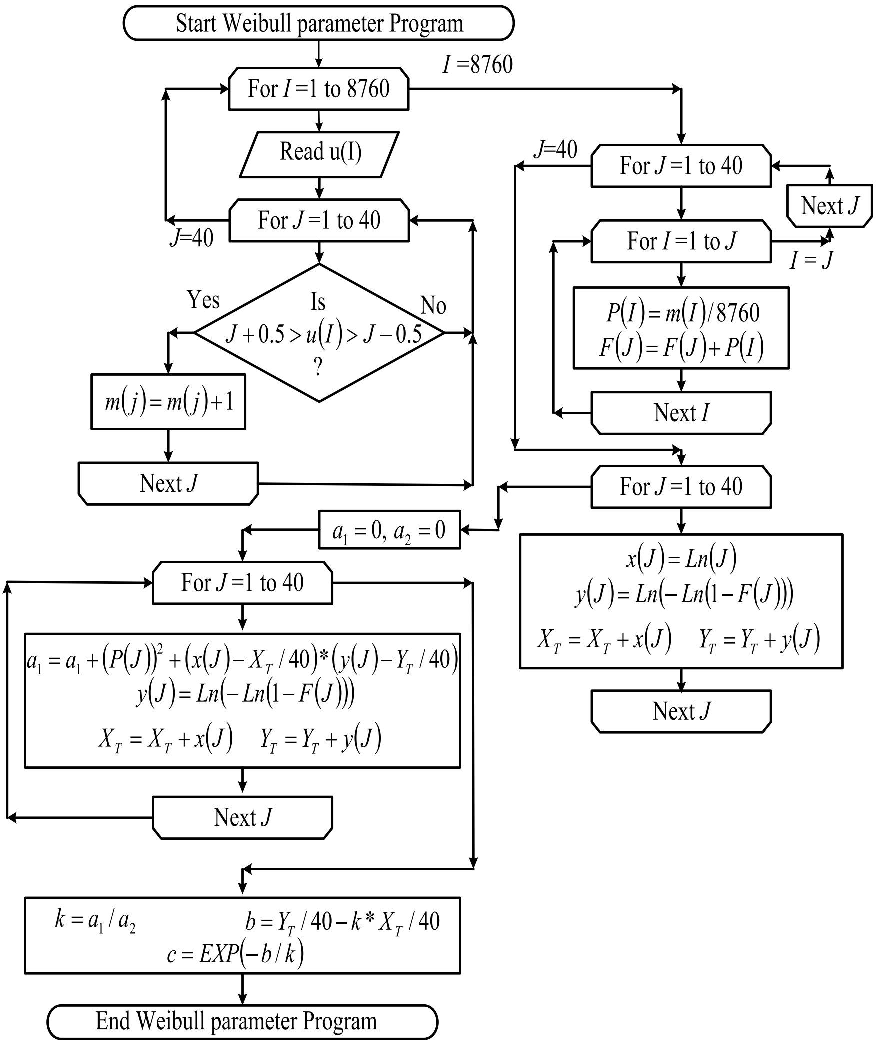


Fig. 4 The flowchart used to determine the Weibull parameters (*c, k*) as discussed in the first subroutine

- Weibull Parameters Determinations.
- Average Power Generated from WES.
- Energy Balance.
- Outputs from Economic Analyses.
- Modified Economic Model.

The proposed computer program is built in Matlab. The data used in the program are the hourly wind speed with their measuring height, the hourly load values, and the

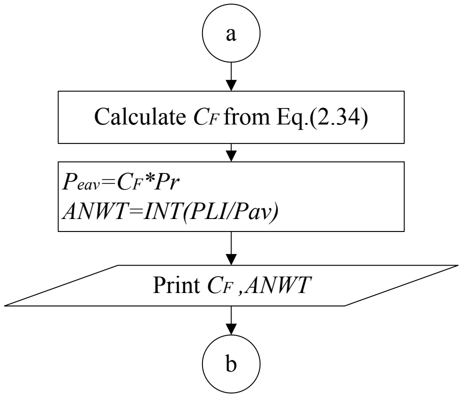


Fig. 5 The flowchart of the second subroutine for calculating the capacity factor and average number of WTs

WTs data and their performance parameters and cost. The optimization procedures of this computer program will be performed to choose the best site and best WT for this site and the cost of generated kWh. All these data are saved in excel files which will be connected to the computer program to handle the design and optimization steps. The proposed program is a built-in generic form to be used with any number of sites and any number of WTs which make it suitable to be used in any place in the world. The following sections show the details of the main program, its input/output, and the detailed description of the subroutines.

3.1 Input Data

The detailed descriptions of the data introduced to the computer program are shown in the following points:

1. The detailed wind speed data of the 32 sites are introduced to the computer program. These data are the hourly wind speeds for 32 sites in Saudi Arabia and the height of the measurement stations. The computer program can handle an unlimited number of sites and an unlimited number of WTs. These data were selected for several years in many places in Saudi Arabia to have high confidence in the results obtained from this program. The summarized data for these selected 32 sites are shown in Table 2.
2. The performance data for the market available 140 WTs are introduced to the new proposed computer program. These performance characteristics of WTs are the rated power, hub height, diameter of swept area, efficiency of the WTs components, cut-in speed, rated speed, cut-out (furling) speed, and the price of WTs. The selected WT types are chosen in different technologies, sizes, and manufacturers. Most of the WTs are selected in size greater than 200 kW.
3. The detailed load characteristics should be introduced to the program; the loads are introduced in hourly fashions. These data are introduced in this chapter.

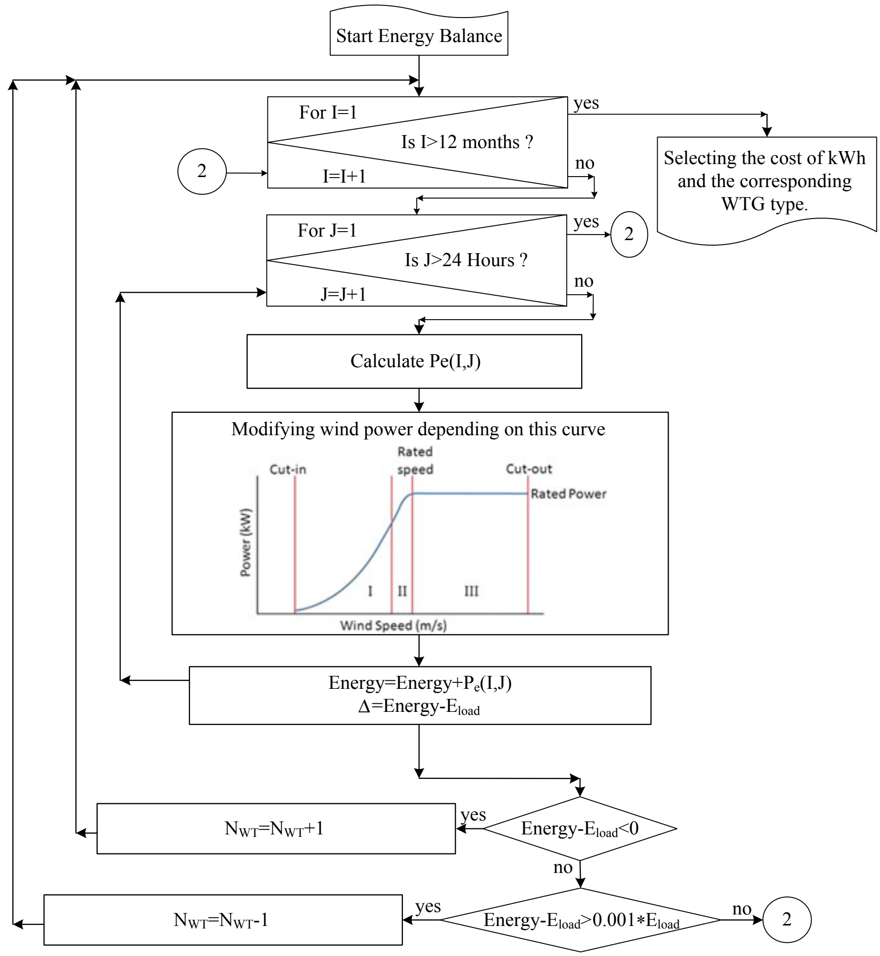


Fig. 6 The flowchart of energy balance subroutine

4. The hourly load profile should be introduced to the computer program. The load data used in this program are collected from actual data of remote communities of one of the villages located at the north of Saudi Arabia called Addfa in the Al-Jouf region province. The hourly data of these loads are introduced to the proposed program. The monthly maximum, minimum, and average loads are shown in Fig. 9.

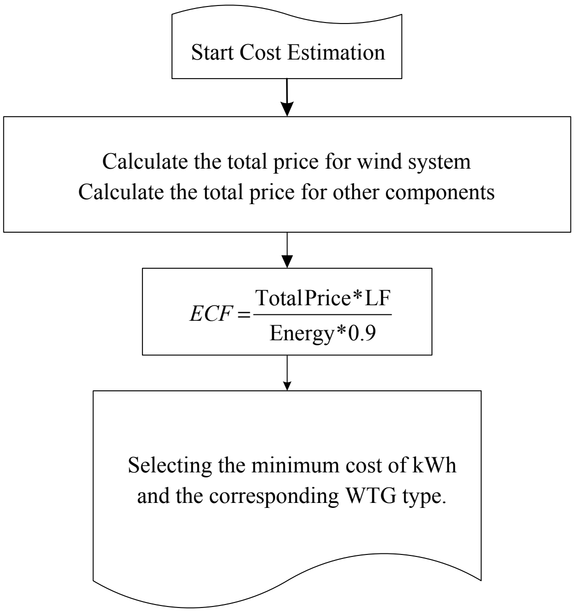


Fig. 7 The flowchart of the energy cost of kWh for each combination and minimum cost of kWh generated and the corresponding WT type

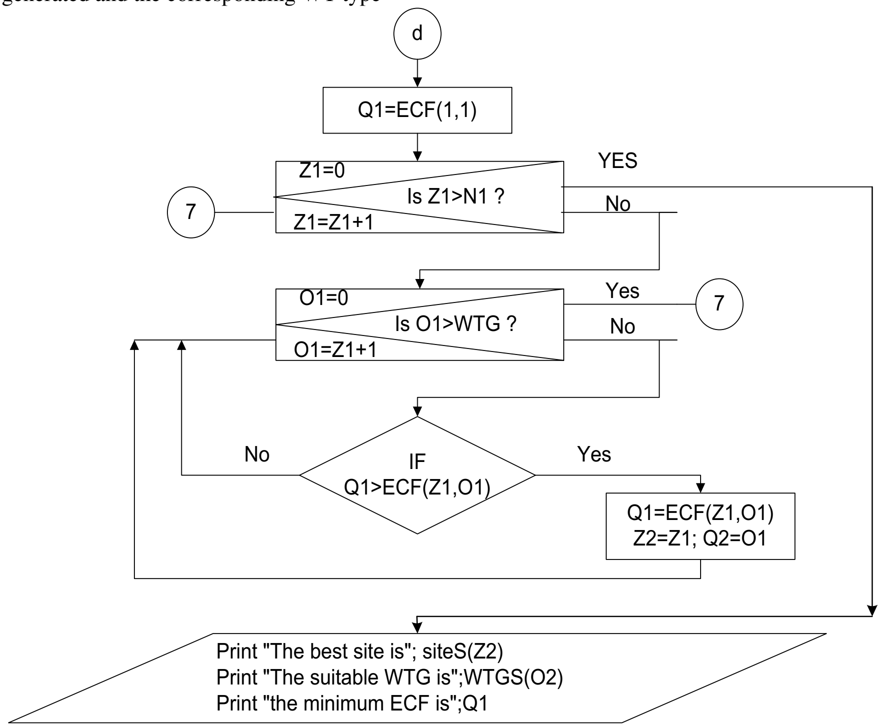


Fig. 8 The flowchart of the final subroutine

Table 2 Summarized data for the selected 32 sites

Site#	Site Name	Longitude	Latitudes	u_{av}	c	k
1	Dammam	50.16	26.4	4.4	4.624301	1.754418
2	Kfia	50.15	26.3	4.41	4.509051	2.755985
3	Dhahran	50.12	26.32	4.31	4.423661	2.920424
4	Al-Ahsa	49.6	25.34	3.7	3.741851	1.877328
5	Sharorah	47.1	17.3	3.31	3.332941	2.556731
6	Riyadh	46.5	24.4	2.95	2.940099	1.939081
7	Qaisumah	46.1	28.18	3.71	3.772909	2.141096
8	Hafer-AlBaten	45.7	28.4	3.33	3.486257	1.609102
9	Asulil	45.6	20.47	3.80	3.978311	2.202145
10	Wadi Al-Dawasser	44.15	20.3	3.5	3.543813	2.193621
11	Najran	44.15	17.35	2.12	2.021776	2.101696
12	Gassim	43.9	26.17	2.91	2.902935	2.116965
13	Rafha	43.5	29.6	3.89	3.973186	2.295766
14	Gizan	42.55	16.9	3.15	3.09359	3.765881
15	Abha	42.51	18.15	3.13	3.088384	2.409208
16	Khamis Mushait	42.43	18.25	3.02	3.000436	2.511597
17	Bisha	42.4	20.25	2.45	2.399268	2.280234
18	Douhlom	42.17	22.72	4.32	4.434125	1.742083
19	Hail	41.6	27.35	3.98	3.48484	2.551401
20	Al-Baha	41.47	20.17	3.46	3.701758	2.495482
21	Taif	40.42	21.27	3.67	3.834777	1.662116
22	Skaka	40.17	29.9	3.82	3.963052	2.220434
23	Al-Jouf	40.1	29.8	3.9	3.678546	2.369471
24	Arar	41.02	30.95	3.63	1.500668	2.097325
25	Makkah	39.84	21.42	1.64	3.011625	2.841229
26	Madinah	39.6	24.45	3.05	3.682481	2.909928
27	Jeddah KAIA	39.2	21.7	3.65	4.263647	2.738051
28	Turaif	38.7	31.7	4.17	3.839341	2.640686
29	Yanbou	38.1	24.1	3.77	4.365416	2.050805
30	Guriat	37.3	31.4	4.24	4.563931	3.43555
31	Wejh	36.75	26.33	4.52	2.587132	1.356426
32	Tabouk	36.57	28.4	2.72	4.713015	3.032604

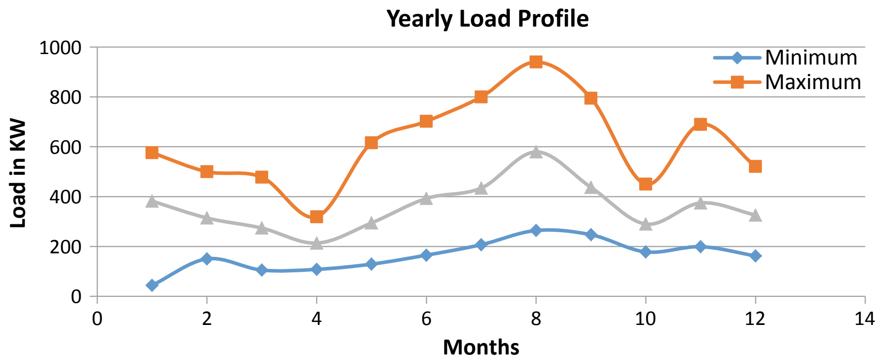


Fig. 9 Monthly minimum, maximum and average load profile for Addfa

3.2 Proposed Computer Program Steps

The block diagram shows the main logic of the proposed computer program as shown in Fig. 3. The part that takes the input data listed above will be introduced to the main computer program. These data should be introduced to the parts of the computer program, and it will be fed to the different subroutines. The main program is controlling the logic of the five subroutines to make different calculations and optimizations. These subroutines perform different parts of the calculations and optimizations and the logic of these subroutines are shown in the following sections.

3.2.1 The Weibull Parameters Determinations "First Subroutine"

This is the first subroutine and it is used to determine the Weibull parameters (scale and shape parameters, c, k). The flowchart used to implement the logic of this subroutine is shown in Fig. 4. The hourly wind speed at the measurement height will be modified from Eq. (2) to the hub height of the WTs. The calculations of Weibull parameters are done using the Eqs. (4)–(14). The results obtained from this subroutine are compared from the same logic used in the excel file and the results obtained from market available programs like the HOMER and the RetScreen software. The results from this subroutine are very near to the results obtained from other programs that give confidence to the obtained results.

3.3 Average Number of WTs and Capacity Factor Determination "Second Subroutine"

The second subroutine is using the results obtained from the first subroutine to this subroutine to calculate the capacity factor, C_F as shown in Eq. (14), the average power of the WT as shown in Eq. (15), and the average number of WT, *ANWT* as shown in (16). It is worth to be noted that the site and WT having the highest number of capacity factor gives an indication for the best option of pairing between the wind turbine and site based on technical perspective meanwhile the cost calculations give us the final and techno-economical results. The average number of wind turbine calculated from this subroutine will be used as a start value to the third subroutine (Energy balance subroutine) to determine the real number of WTs needed to cover the hourly load within completely.

3.4 Energy Balance "Third Subroutine"

The subroutine is used to check the adequacy of the hourly generated power from the WES to feed the loads. The generated power from the WES is shown in Eq. (17). The overall efficiency of the WT is shown in Eq. (18). If the case of the load requirement is greater than the generated power from the WES, the deficit power will be supplied from the electric utility. Meanwhile, in the case of the hourly generated power from the wind energy system is greater than the power required by the loads, the extra power will be transmitted to the electric energy. The energy balance subroutine should assure that the energy fed to the electric utility is equal to the energy received from the utility grid. This logic is modeled in the Eqs. (19), (20), and (21).

The output power from WES is given by:

$$P_e = \frac{1}{2}\rho * A * u^3 * N_t * \eta_0 \tag{17}$$

$$\eta_o = C_p\, \eta_m \eta_g \tag{18}$$

$$\text{If } P_e > P_L, \text{ Then } P_T = P_e - P_L, \text{ and } P_f = 0 \tag{19}$$

$$\text{If } P_e < P_L, \text{ Then } P_F = P_L - P_e \text{ and } P_T = 0 \tag{20}$$

For energy balance the following conditions must be satisfied;

$$\sum_{i=1}^{8760} P_e(i) - \sum_{i=1}^{8760} P_L(i) = 0 \quad \text{and} \quad \sum_{i=1}^{8760} P_T(i) = \sum_{i=1}^{8760} P_F(i) = 0 \tag{21}$$

3.5 Economic Analyses "Fourth Subroutine"

3.5.1 Overview of Outputs

Four main outputs are applicable to the economic analysis of prospective wind farms. These include the *NPV*, the present cost of energy, and the time to recover capital. This subroutine will handle the calculations of the cost of energy for the WTs and sites under study. The flowchart of this subroutine is shown in Fig. 7. Several works are already presented as a first step to harness this alternated energy source and to use this to generate electricity at a large and economical scale. A detailed technique is used to calculate the generated kWh from WES. All the details of the WES are considered in this methodology to a precise estimation for the cost of kWh generated from the WES. This methodology is applied for all sites and all wind turbines. The site and WT corresponding to the lowest cost will be selected as the best option. Also, the lowest cost associated with each site can be used to select the best WT for this site. The results obtained from the cost analysis methodology can produce many results as will be introduced in the following sections.

The price of the kW rated power of the WT is used as $700/kW. Equation (22) is used to determine the total price of WTs by multiplying the price per kW by the number of WTs and the rated power of the WT. The price of the microprocessor (TPMIC), the price of main substation (TPMS), the price of the modem for remote control in central control station (TPCCS), and the price of the transmission line (TPTL) are 2.3 $/kW, 10.4 $/kW, 4.16 $/kW, and 1.3 $/kW, respectively, and the total values of these items are shown in Eqs. (22)–(26).

$$\text{TPWT} = \$700 * NWT * P_r \tag{22}$$

$$\text{TPMIC} = \$2.3 * NWT * P_r \tag{23}$$

$$\text{TPMS} = \$10.4 * NWT * P_r \tag{24}$$

$$\text{TPCCS} = \$4.16 * NWT * P_r \tag{25}$$

$$\text{TPTL} = \$1.3 * NWT * P_r \tag{26}$$

where:

TPWT Total price of WTs.
TPMIC Total price of microcontrollers.
TPMS Total price of the main substation.
TPCCS Total price of remote control in the central control station.
TPTL Total price of the transmission lines.

The maintenance and operation cost is taken as 10% of the total cost of the WES as shown in (27). The energy cost figure (*ECF*) can be obtained from using the total cost of the WES as shown in (28) and divide it by the yearly generated energy multiplied by the levelization factor as shown in (29). The total price of WES can be calculated from (27) and (28) and the *ECF* can be determined from (30).

$$\text{Total Price} = 1.1 * (\text{TPWT} + \text{TPMIC} + \text{TPMS} + \text{TPRC} + \text{TPCCS} + \text{TPTL}) \tag{27}$$

$$\text{Total Price} = 1.1 * (718.16 * NWT * \text{Pr}) \tag{28}$$

$$ECF = \frac{\text{Total Price} \; * LF}{YE * 0.9} \tag{29}$$

where:

LF is the levelization factor.

The levelization factor is 0.177 based on a 12% interest rate and 10 years recovery time.

3.5.2 Modified Economic Model

The design of wind energy systems should be based on techno-economical methodology where the cost of the generated energy is the most important issue. The WT may work efficiently in economical in some sites, but it may not work in some other sites. For this reason, the selection of the WT and the site should be based on the cost of energy. To obtain the highest available energy, the WT can have enormous blades and wide swept area by these blades; however, this not economical because the wide-area required a huge and strong tower and high technology for manufacturing the blades and other components of the WTs and all these come at a cost. Also, the most efficient turbine may not be the cheapest to produce energy because it may be suitable for one site and is not suitable for another one. To compare the cost of energy produced by a turbine, some economic analyses need to be performed.

Different economical methodologies have been introduced in the literature to calculate the expected price of generated energy from the WES. Some methodologies used the NPV to perform the calculations of the cost of kWh [54, 55]. These methodologies determined the Levelized Cost of Energy, *LCE* to calculate the cost of energy as shown in (30) [56]. The value of LEC can be determined by dividing the total present value multiplied by the capital recovery factor, *CRF*.

$$LCE = \frac{TPV * CRF}{AE} \tag{30}$$

where TPV is the total present value of the wind energy system, *AE* is the yearly loads connected to the WES. The *CRF* is the capital recovery factor and can be obtained from (31).

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1} \tag{31}$$

Equation (32) is used to determine the TPV by adding the whole cost and subtract the components' salvage values at the beginning of the operation of the WES.

$$TPV = IC + RC + OMC - PSV \tag{32}$$

where *IC* is the initial capital cost of the whole system, *RC* is the replacement cost, *OMC* is the operation and maintenance cost, and *PSV* is the present value of scrap

[56]. Detailed values of each item of Eq. (32) are shown and discussed in the following sections.

A. **Initial Capital Cost**

The initial cost is collecting the price of all components of the wind energy system based on the market price for accurate results of the generated energy cost. The total cost of the WES is called the initial capital cost (IC). The IC is the sum of the price of WTs, installation cost, price of other components like a transmission line, transformers, and protection system. The civil work cost, and the components used in the wind energy system are estimated to be 20% of the price of WTs [57]. Based on these assumptions, the initial cost is determined from (33).

$$IC = 1.2 * WT_P * P_R * NWT + P_{inv} * INV_P \tag{33}$$

where WT_P is the price of kW of the rated power of WT, P_r is the rated power of the WT, NWT is the total number of WT required for the wind energy system. P_{inv} is the rated power of the inverter, and INV_P is the price of inverter per kW.

B. **Replacement Cost**

There are many components of the wind energy system that should be replaced during the lifetime of the project. These components should be determined at the start of the project and its present value at the beginning of the project should be determined. The net present values of components (Replacement cost, RC) should be calculated based on the interest rate (r) and inflation rate (i) as shown in (34) [57, 58]:

$$RC = \sum_{j=1}^{N_{rep}} \left(C_{RC} * C_U * \left(\frac{1+i}{1+r} \right)^{T*j/(N_{rep}+1)} \right) \tag{34}$$

where, C_{RC} is the capacity of the replacement unit (kW for WTs, and inverters, kWh, etc.), C_U is the unit price cost ($/kW for WT and inverters, $/kWh for battery), N_{rep} is the number of replacements during the system life period T.

C. **Operation and Maintenance Cost**

Many components of the wind energy system need an effective maintenance program during the lifetime of the project. The cost of maintenance during the lifetime of the project should be estimated and its net present value should be determined. Two parts of the wind energy systems need intensive maintenance programs which are the WTs and the power electronics converter. The maintenance of the WTs is estimated as 5% of the total cost of WTs, meanwhile, the maintenance cost of the inverter is estimated to be 1% [59]. Another study estimated the operation and maintenance cost (OMC) of the whole wind energy system to be 1% of the total cost of the wind energy system [56]. Some other studies [60] used fixed cost for each kW of the components such as

100 \$/kW for WTs and 1% of the cost of the inverter. The study shown in [61] used the annual maintenance cost of WT of \$20/kW. Reference [62] used the annual MOC to be \$10/kW for WTs. Some studies linked the OMC to the operation of the wind energy system by estimating the OMC as 1% of the total cost of kWh generated from the wind energy systems [63, 64]. The present value of OMC of the wind energy system used the total amount of maintenance and it uses the interest rate and inflation rate to estimate its value as shown in (36) [54]:

$$OMC = OMC_0 * \left(\frac{1+i}{r-i}\right) * \left(1 - \left(\frac{1+i}{1+r}\right)^T\right), \quad r \neq i \tag{35}$$

D. **The Present Salvage Value**

The replacements during the operation of the project and the price of the components at the end of the project should be taken into considerations. The price of these components should be determined as revenue at the start of the project taking into consideration the interest rate and inflation rate as shown in (36) [14, 56]. This salvage value (SV) is estimated to be 10% of WT, 20% of the power electronics converters and batteries, and other components will not have a value at the end of its use [14]. In this study, the SV has been taken as 20% for WTs, and 10% for the power conditioning components. The present value of SV should be calculated at the beginning of the project taking into considerations the interest rate and failure rate which is called the present salvage value (*PSV*) as shown in (36)

$$PSV = \sum_{j=1}^{N_{rep}+1} SV * \left(\frac{1+i}{1+r}\right)^{T*j/(N_{rep}+1)} \tag{36}$$

where SV is the scrap value, i is the inflation rate, r interest rate, N_{rep} is the number of different components replacements over the system life period T.

3.6 Selecting the Best Site and Best Wind Turbine for each Site "Fifth Subroutine"

This part of the program is used to extract the cost results of kWh generated from all options of sites and WTs as shown in Fig. 8. The minimum cost will be selected as the best option and the site and WT associate with this lowest cost will be selected to be used as the best matching between the sites and WT types. Many other useful results can be extracted from this subroutine like the best WT for each site based on the minimum cost for each site.

4 Output Results

The new proposed program has been used with 32 sites in Saudi Arabia and 140 market available WTs. The program can perform perfect site matching with WT type. The selection of suitable WT type has been carried out depending on the minimum energy price. An accurate cost estimation technique has been introduced to get accurate results. Many information can be extracted from this computer program. Some salient results have been presented in this report. Enormous helpful results can be also extracted from this program and it will not be displayed in this report due to the limitation of the report size. The enormous input data (32 sites wind speed data and 140 WT performance parameters) can perform an accurate wind energy map for Saudi Arabia. An excel program is used to implement the logic of this program to validate the results obtained from this subroutine. The output results from this computer program are shown in the following:

The 32 sites and the 140 WT types are used to draw a relationship between the rated wind speed and cut-in wind speeds as shown in Fig. 10. Using curve fitting of this relation to the first-order polynomial, the relation shown in (37) can be used to model this relation. The rated wind speed is directly proportional to the cut-in wind speed and the minimum and maximum cut-in wind speed are 2 m/s and 4 m/s, respectively. Meanwhile, most of the cut-in wind speed of the WTs is 3 m/s. Moreover, the minimum and maximum values of rated wind speed of WTs are 10 m/s and 15 m/s, respectively.

$$u_r = 1.2679\ u_c + 8.5227 \tag{37}$$

The relationship between the Weibull scale parameter, c against the hub heights of WTs in five sites is shown in Fig. 11. It is clear from this figure that the Weibull scale parameter is linearly proportional to the hub height of the WTs.

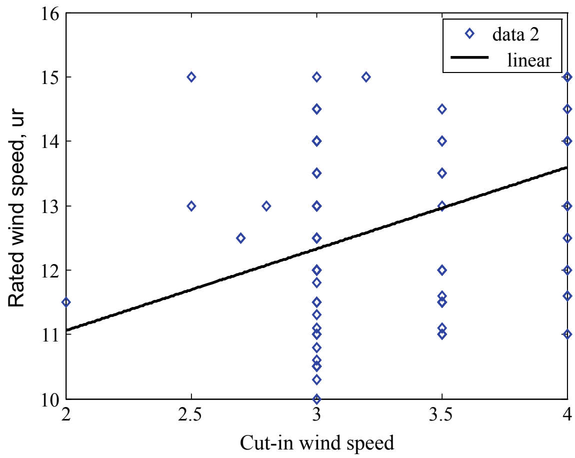


Fig. 10 The rated wind speed along with the cut-in wind speed of WTs

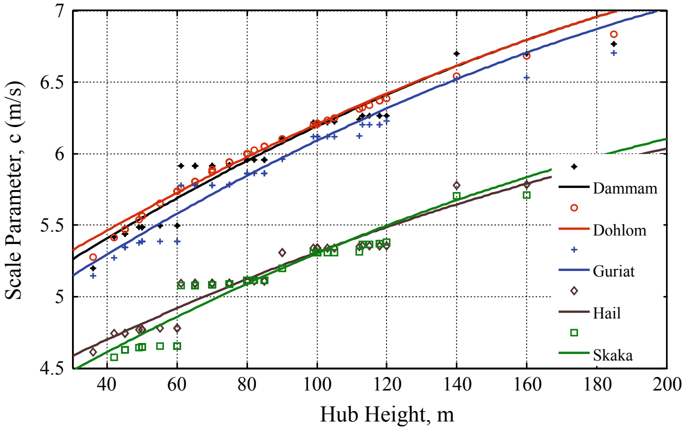


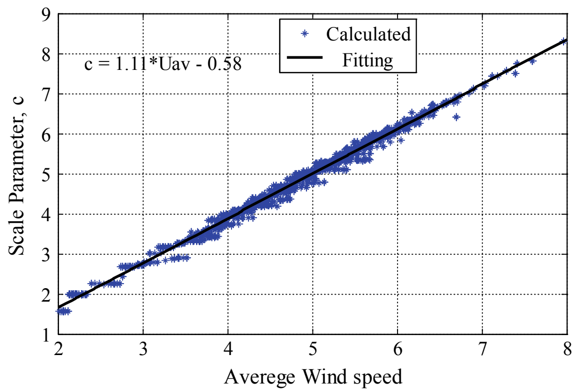
Fig. 11 The variation of Weibull scale parameter, c, and the hub height of WT, *h* for the best five sites among the 32 sites under study

Another very useful relationship between *c* and *ur* can be obtained from Fig. 12. This relation shows that the relationship showing *c* and u_r is linearly proportional. This relation is shown in Eq. (38). This relation is very helpful to the researchers and designers to determine the Weibull scale parameter directly from average wind speed without using the sophisticated calculations shown in the first subroutine.

$$c = 1.11 * u_{av} - 0.58 \quad (38)$$

Similar studies have been introduced in the literature to get this important relationship between the Weibull scale factor and the average wind speed of the site. One of these relations used the Gamma function to get another relation between average wind speed and Weibull parameters as shown in Eq. (39) [2]. Another equation introduced in (40) to model this relation between the Weibull scale parameters

Fig. 12 The variation of the Weibull scale parameter, *c* along with average wind speed for WTs and sites under study



and average wind speed [65].

$$\frac{u_{av}}{c} = \Gamma(1 + \frac{1}{k}) \tag{39}$$

$$c = 1.12 * u_{av} \tag{40}$$

The Weibull parameters are used to determine the capacity factor of the wind energy system. The value of the capacity factor is very important where it is counted as the technical matching factor because the high value of the capacity factor means the high performance of the WT in this site. So, the capacity factor can be drawn based on the average wind speed and the rated wind speed as shown in Fig. 13. This relation is extracted from using the 32 sites and the 140 WTs used in this study. This relation shows that the highest capacity factor can be achieved at high average wind speed and low rated wind speed of the WT and vice versa.

The relation between the capacity factor, C_F and u_{av}/u_r for all sites under study and all WT types is shown in Fig. 14. This figure implies that the capacity factor increases with increasing the value of u_{av}/u_r for all sites and all WT types. So it is recommended to use sites with the highest average wind speed, and it is also recommended to use WT with the lowest rated wind speed to get the highest capacity factor. The highest capacity factor can be translated into lower cost and lower price of the generated kWh. It is also clear from this figure that the capacity factor increases with increasing the ratio of average and rated wind speed till u_{av}/u_r equal approximately to 1.22 after that the capacity factor will be reduced. So it is not recommended to install WT in any site with an average wind speed greater than 1.22 times the average wind speed.

Figure 15 shows the relationship between the energy price and capacity factor for 32 sites and 140 WT types. The energy cost is inversely proportional to the capacity

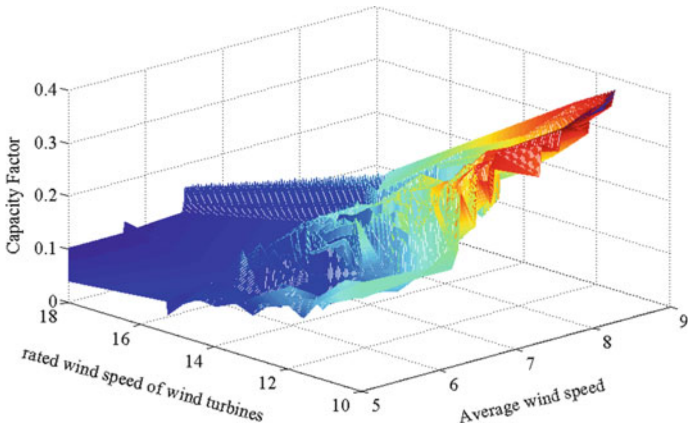


Fig. 13 3-D graph showing the relation between the capacity factor along with the rated wind speed of the WT and the average wind speed of the sites under study

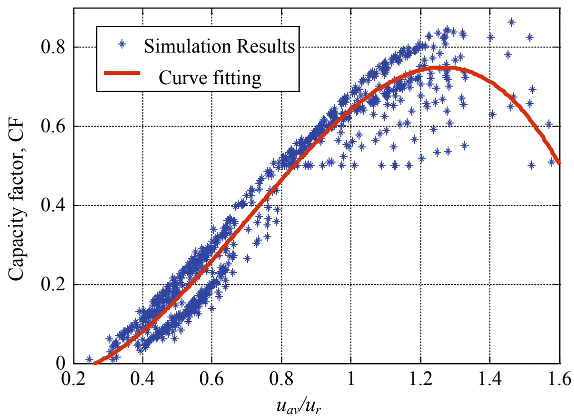


Fig. 14 The relation between u_{av}/u_r and capacity factor

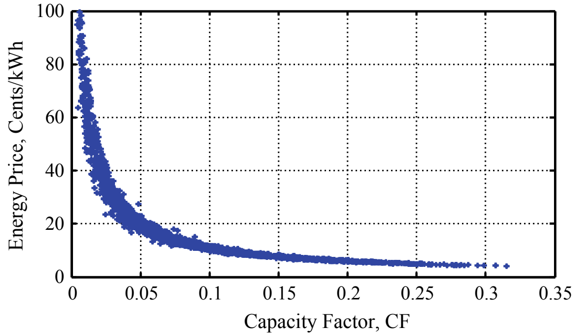


Fig. 15 The energy cost for the 32 sites and 140 WTs under study along with the capacity factor

factor i.e., as the capacity factor increases the energy price decreases. Also, Fig. 16 shows the relation between the energy price (Cents/kWh) and the (u_{av}/u_r) for 32 sites and 140 WT types. This figure emphasizes that the energy price is inversely proportional to (u_{av}/u_r).

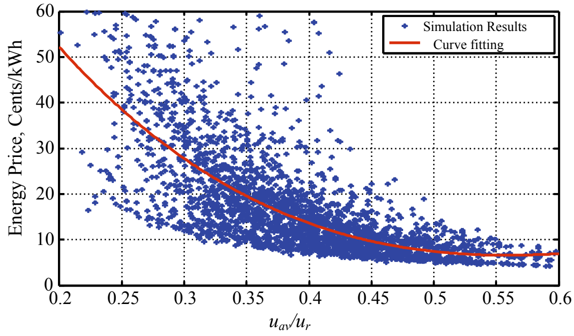


Fig. 16 The energy price in Cents/kWh for 32 sites and 140 WT along with (u_{av}/u_r)

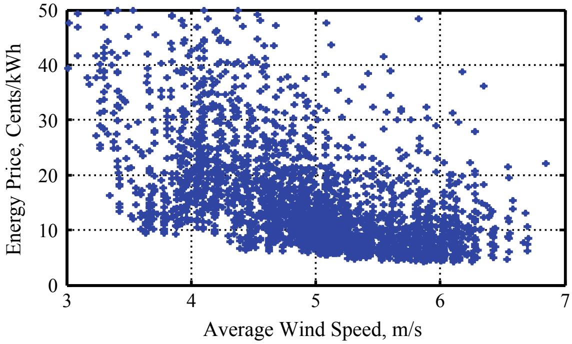


Fig. 17 The relation between the energy price and average wind speed for 32 sites and 140 WTs

Figure 17 shows the relation between the energy price and average wind speed for 32 sites and 140 WT types. The energy price is inversely proportional to the average wind speed i.e., as the average wind speed increases the energy price decreases. As an example, Fig. 18 shows the relation between energy price (Cents/kWh) and the average wind speed for 32 sites with WT #1. This figure emphasizes this inverse relationship between energy price and average wind speed.

Table 3 shows site information in order from best to worst depending on *ECF*. It is clear from this table that the best site among these 32 sites is Dammam with 4.155073 Cents/kWh and the next four sites are Douhlom, Guriat, Hail, Skaka with 4.395947, 4.395947, 4.576602, and 5.239005 Cents/kWh, respectively. These best five sites results will be discussed in detail and will be compared with other sites in the following discussion. The most interesting points in these results are that all of these sites do not have the highest average wind speed but at least these sites have good wind speed with respect to other sites. Also, the price of kWh generated from Douhlom and Guriat sites with WT #2 is 5.8% greater than the price of kWh

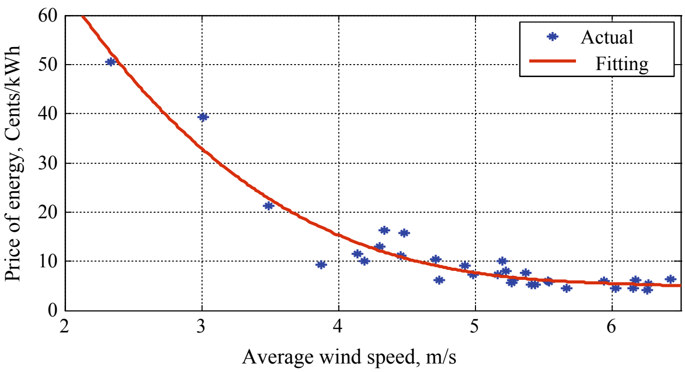


Fig. 18 The relation between energy price Cents/kWh and the average wind speed for 32 sites with WT #1 as an example

Table 3 Sites information in order from best to worst depending on ECF

Site Order	Site name	Best WT		Average Wind speed	*ECF*	% increase from the best site, 'Dammam'
		WT #	WT Name	m/s	C/kWh	
1	Dammam	2	Goldwind_3	4.4	4.155073	0.0
2	Douhlom	2	Goldwind_3	4.32	4.395947	5.8
3	Guriat	2	Goldwind_3	4.24	4.395947	5.8
4	Hail	1	Acciona_6	3.98	4.576602	10.1
5	Skaka	2	Goldwind_3	3.82	5.239005	26.1
6	Asulil	1	Acciona_6	3.8	5.299224	27.5
7	KFIA	1	Acciona_6	4.41	5.419661	30.4
8	Al-Ahsa	1	Acciona_6	3.7	5.660534	36.2
9	Al-Jouf	1	Acciona_6	3.9	5.780971	39.1
10	Dhahran	3	Goldwind_4	4.31	6.021845	44.9
11	Rafha	1	Acciona_6	3.89	6.021845	44.9
12	Turaif	1	Acciona_6	4.17	6.021845	44.9
13	Qaisumah	1	Acciona_6	3.71	6.142282	47.8
14	Hafer-Albate	1	Acciona_6	3.33	6.142282	47.8
15	Wejh	1	Acciona_6	4.52	6.383155	53.6
16	Wadi	1	Acciona_6	3.5	7.226214	73.9
17	Arar	1	Acciona_6	3.63	7.226214	73.9
18	Yanbou	1	Acciona_6	3.77	7.587525	82.6
19	Taif	1	Acciona_6	3.67	8.069273	94.2
20	Al-Baha	1	Acciona_6	3.46	9.032767	117.4
21	Tabouk	1	Acciona_6	2.72	9.273642	123.2
22	Riyadh	1	Acciona_6	2.95	9.996264	140.6
23	Jeddah	1	Acciona_6	3.65	9.996264	140.6
24	Sharorah	1	Acciona_6	3.31	10.47801	152.2
25	Abha	1	Acciona_6	3.13	11.20063	169.6
26	Gassim	1	Acciona_6	2.91	11.44151	175.4
27	Khamis	1	Acciona_6	3.02	13.00718	213.0
28	Madinah	1	Acciona_6	3.05	16.25898	291.3
29	Bisha	1	Acciona_6	2.45	21.1969	410.1
30	Gizan	63	Fuhrlander_4	3.15	29.00522	598.1
31	Najran	1	Acciona_6	2.12	39.38287	847.8
32	Makkah	34	AWE_1	1.64	129.8009	3023.9

generated from the Dammam site with WT #2. Also, it is clear that the price of kWh generated from the Hail site with WT #1 is 10.1% greater than the price of kWh generated from the Dammam site with WT #2. Also, the price of kWh generated from the Skaka site with WT #2 is 26.1% greater than the price of kWh generated from the Dammam site with WT #2. Also, it is clear from the table that the worst sites in wind energy applications are Madinah, Bisha, Gizan, Najran, and Makkah where the price of kWh generated from these sites with the best WT for each of them are 16.25898, 21.1969, 29.00522, 39.38287, and 129.8009 Cents/kWh, respectively. These sites are not good option to install the WES on it. Also, it is noted that the cost of the generated kWh from the WES in these five sites are almost 4, 5, 7, 9.5, 31 times the cost of kWh generated from the Dammam site with WT #2.

Many interesting information and recommendations can be concluded from Table 4. The following points summarized the salient information and recommendations that can be extracted from the above table.

Table 4 Sites in order from best to worst depending on ECF

Site Order	Site name	Location	Average Speed	Best WT									
				1	2	3	4	5	6	7	8	9	10
1	Dammam	EM	4.4	2	1	113	3	54	53	17	88	99	19
2	Dohlom	WS	4.32	2	1	3	113	54	53	97	17	99	63
3	Guriat	WN	4.24	2	1	3	113	54	53	17	19	88	97
4	Hail	MN	3.98	1	2	113	3	54	53	88	17	99	63
5	Skaka	MN	3.82	2	1	113	3	54	53	17	88	97	99
6	Asulil	MM	3.8	1	2	113	3	54	53	88	17	97	99
7	KFIA	WN	4.41	1	3	2	54	113	53	63	17	99	97
8	Al-Ahsa	EM	3.7	1	2	113	3	54	53	88	17	99	19
9	Al-Jouf	MN	3.9	1	2	113	3	54	53	88	17	19	97
10	Dhahran	EM	4.31	3	1	2	54	53	17	97	99	113	63
11	Rafha	WN	3.89	1	2	3	113	54	53	63	19	97	17
12	Turaif	WN	4.17	1	2	3	54	113	53	17	19	97	99
13	Qaisumah	EN	3.71	1	2	113	3	54	53	88	19	17	99
14	Hafer Al-Baten	EN	3.33	1	2	113	3	35	36	34	54	53	88
15	Wejh	WN	4.52	1	3	54	2	53	17	99	19	97	113
16	Wadi	MS	3.5	1	2	113	3	54	53	88	19	17	99
17	Arar	WN	3.63	1	2	113	3	54	53	88	63	19	97
18	Yanbou	WM	3.77	1	2	3	113	54	53	63	19	97	17
19	Taif	WM	3.67	1	2	113	3	63	54	53	19	17	88
20	Al-Baha	WN	3.46	1	2	113	3	54	88	63	19	53	17
21	Tabouk	WN	2.72	1	2	35	36	34	113	3	54	88	53
22	Riyadh	MM	2.95	1	2	113	3	54	88	53	34	35	36
23	Jeddah	WM	3.65	1	2	3	113	63	54	19	53	88	17
24	Sharorah	ES	3.31	1	2	113	3	54	88	63	19	53	17
25	Abha	WS	3.13	1	2	113	63	3	88	54	19	53	29
26	Gassim	MM	2.91	1	2	113	3	88	54	53	34	35	36
27	Khamis	WS	3.02	1	2	113	3	88	63	54	19	53	29
28	Madinah	WM	3.05	1	2	113	63	88	3	19	54	29	53
29	Bisha	MM	2.45	1	2	113	88	35	36	34	3	86	54
30	Gizan	WS	3.15	63	2	1	113	88	67	19	3	29	54
31	Najran	WS	2.12	1	2	34	35	36	113	88	3	86	54
32	Makkah	WM	1.64	34	35	36	1	2	113	122	3	86	67

Hint: E=East, W=West, M=Middle, N=North, S=South

- WTs # 1, 2, 3, 113, and 54 are shown among the best 10 WT types for all sites under study. So, it is recommended to use any one of these WT types for sites that do not have a design study or unavailable wind speed data.
- The best two WTs in most sites are WTs # 1 and 2. This is the case in 30 sites except for Gizan and Makkah because these two sites have very low wind speeds. So, it is recommended to use WTs # 1, 2 in most of the sites in Saudi Arabia except sites with very low average wind speed.
- WT # 2 is the best selection for sites with good average wind speeds such as Dammam, Douhlom, Guriat, and Skaka. Also, the second option for these sites is WT #1. So, it is recommended to use WT #2 in sites with average wind speed greater than 4 m/s in 10 m elevation.
- WT #1 is the best option for sites with medium average wind speed and WT #2 is the second-best option in most of these cases. So, it is recommended to use WT #1 in sites with average wind speed lower than 4 m/s and greater than 2.45 m/s in 10 m' elevation except for Gizan, Dhahran, and Skaka**.**
- WTs # 34, 35, and 36 are the best options for the sites having very low average wind speeds such as Makkah and Najran. Where these WT types were never shown among the best 10 WTs except with sites having average wind speed lower than 3 m/s. So, it is recommended to use WTs # 34, 35, and 36 for sites lower

than 2.4 m/s and it is acceptable to use them for average wind speed between 2.4 and 3 m/s over 10 m elevation.

4.1 Detailed Results from Best Five Sites

Detailed results of the best five sites are shown in the following sections. These results are focused on the comparison between the best and worst WT types; also a comparison between the five best and five worst WTs for each site will be displayed. Also, a list for the best 10 WT types and 10 worst WT types will be shown in tables for these five sites.

4.1.1 Detailed Results from Dammam Site

It is clear from the results of the new proposed computer program that has been summarized in Tables 5 and 6 that the Dammam site is the best site for wind energy applications. The best WT type for the Dammam site is WT #2. The price of kWh generated from Dammam with WT #2 is 4.155073 Cents/kWh. The worst WT that can be used in Dammam is NEPC_2 (WT #125) with 12.766 Cents/kWh which shows that it is three times the price of kWh generated in Dammam with WT #2. The main reason in the big difference in the price of kWh is because most of the available wind speed of the Dammam site is used to generate power from WT #2 but most of these

Table 5 The sest 10 WT types in the Dammam site

WT		u_c	u_r	u_f	c	k	C_F	*ECF*
Name	#							
Goldwind_3	2	3	10.3	22	6.220	1.709	0.315	4.155
Acciona_6	1	3	10.6	20	6.264	1.695	0.307	4.215
HZ_WindPR_3	113	3	10.5	25	6.220	1.709	0.307	4.255
Goldwind_4	3	3	9.9	22	5.918	1.790	0.299	4.276
Envision_4	54	3	10	25	5.913	1.792	0.294	4.396
Envision_3	53	3	10.5	25	5.957	1.772	0.279	4.456
Acciona_3	17	3	10.5	20	5.956	1.772	0.278	4.516
Goldwind_2	88	3	11	22	6.220	1.709	0.288	4.516
Guodian_3	99	3	10.5	25	5.956	1.772	0.279	4.516
Acciona_5	19	3.5	11	25	6.264	1.695	0.276	4.577

Table 6 The detailed results for the worst 10 WT types in the Dammam site

WT Name		u_c	u_r	u_f	c	k	C_F	*ECF*
Name	#							
GC_China_Turbine_Corp_1	74	4	15	25	5.913	1.792	0.126	9.153
GC_China_Turbine_Corp_2	75	4	15	25	5.913	1.792	0.126	9.153
GC_China_Turbine_Corp_3	76	4	15	21	5.913	1.792	0.126	9.193
Gamesa_2	68	4	15	25	5.912	1.792	0.126	9.380
Gamesa_3	69	4	15	25	5.912	1.792	0.126	9.384
Ecotecnia_2	44	4	14.5	25	5.440	1.681	0.119	9.659
NEPC_1	124	4	15	25	5.440	1.681	0.111	10.234
Southern_Wind_Farms	128	4	15	25	5.440	1.681	0.111	10.234
NEPC_3	126	4	15	25	5.198	1.746	0.092	11.305
NEPC_2	125	4	17	25	5.440	1.681	0.089	12.766

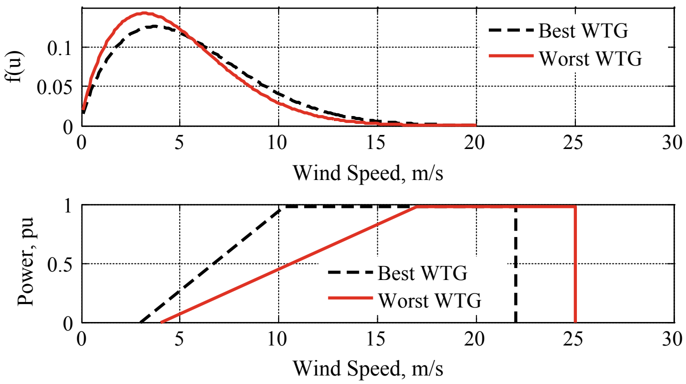


Fig. 19 Comparison between the best and worst WT types for the Dammam site

speeds are not used to generate power from WT #125. These conclusions are shown very clear in Fig. 19. This figure shows a comparison between the best WT type for Dammam (WT #2) and the worst WT type for this site (WT #125). The first curve shows the speed distribution facing each WT type in the Dammam site. The second curve shows the generated power against wind speed for WT #2 and WT #125. It is clear from this figure that most of the speed distribution for Dammam is lying within the generated area of WT #2. But, most of the speeds are shown below the cut-in speed of WT #125 and there is no considerable speed over the rated speed of WT #125. The same results can be concluded from the next two figures where Fig. 20 and Fig. 21 show the distribution of wind speed and the power characteristics against wind speed for the best and worst five WTs for the Dammam site, respectively.

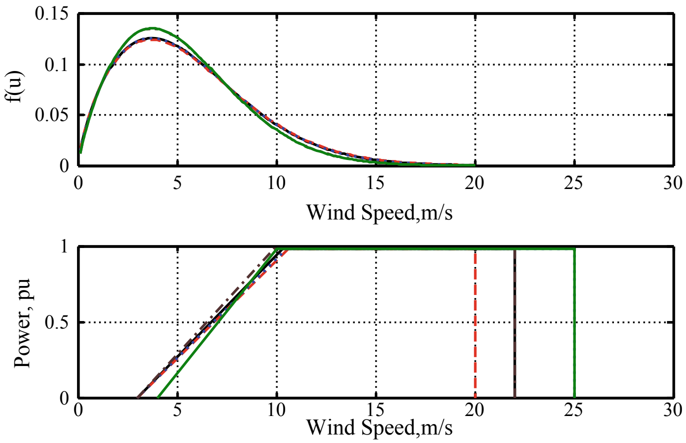


Fig. 20 Best five WT types in the Dammam site

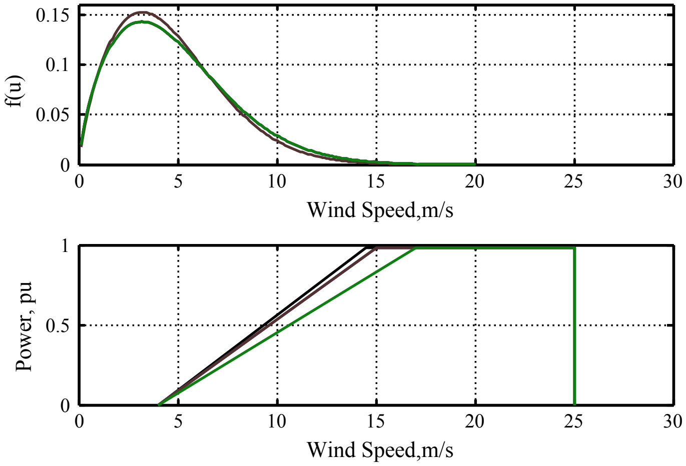


Fig. 21 Worst five WT types for Dammam site

These two figures show that most of the speed in the Dammam site is lying within the generated power of five best WTs but most of the speeds are not lying within the generated power area of the worst five WTs for the Dammam site.

Tables 5 and 6 show the list of the best 10 WTs and the worst 10 WTs for Dammam. These tables also show the WTs name, numbers, specifications, Weibull parameters, capacity factor, and the cost of energy generated from each WT. Moreover, the cost of energy is inversely proportional to the capacity factor in each case. Also, it is better to use WT #2 in the Dammam site for the minimum cost of generated energy. Also if a wrong WT type like WT #125 is used instead of WT #2 in Dammam site, the price of the generated kWh will be more than three times the price associated with WT #2. So it is not recommended to use any one of the worst WT types shown in Table 6 on the Dammam site.

4.1.2 Detailed Results from Douhlom Site

It is clear from the results of the new proposed computer program that has been summarized in Tables 7 and 8 that the Douhlom site is the second best site for wind energy applications. The best WT type for the Douhlom site is WT #2. The price of kWh generated from Douhlom with WT #2 is 4.396 Cents/kWh. The worst WT that can be used in Douhlom is NEPC_2 (WT #125) with 19.36 Cents/kWh which is clear that it is more than four times the price of kWh generated in Douhlom with WT #2. The main reason of the big difference in the price of kWh is because most of the available wind speed of the Douhlom site is used to generate power from WT #2 but most of these speeds are not used to generate power from WT #125. These conclusions are shown very clear in Fig. 22. This figure shows a comparison between the best WT type for Douhlom (WT #2) and the worst WT type for this

Table 7 The detailed results for the best 10 WT types in the Douhlom site

WT Name	#	u_c	u_r	u_f	c	k	C_F	ECF
Goldwind_3	2	3	10.3	22	6.206	2.130	0.277	4.396
Acciona_6	1	3	10.6	20	6.371	2.137	0.277	4.456
Goldwind_4	3	3	9.9	22	5.942	2.120	0.272	4.456
HZ_WindPR_3	113	3	10.5	25	6.206	2.130	0.267	4.577
Envision_4	54	3	10	25	5.872	2.115	0.260	4.637
Envision_3	53	3	10.5	25	6.052	2.127	0.253	4.757
Guodian_1	97	3	10.5	25	5.999	2.127	0.248	4.817
Acciona_3	17	3	10.5	20	5.999	2.127	0.248	4.878
Guodian_3	99	3	10.5	25	5.999	2.127	0.248	4.878
Fuhrlander_4	63	3.5	11.5	25	6.685	2.150	0.250	4.918

Table 8 The detailed results for the worst 10 WT types in the Douhlom site

WT Name	#	u_c	u_r	u_f	c	k	C_F	ECF
GC_China_Turbine_Corp_2	75	4	15	25	5.872	2.115	0.094	12.285
GC_China_Turbine_Corp_3	76	4	15	21	5.872	2.115	0.094	12.285
Ecotecnia_3	45	4	14.5	25	5.656	2.110	0.091	12.586
Gamesa_3	69	4	15	25	5.805	2.111	0.091	12.660
Gamesa_2	68	4	15	25	5.805	2.111	0.091	12.665
Ecotecnia_2	44	4	14.5	25	5.472	2.097	0.083	13.633
NEPC_1	124	4	15	25	5.472	2.097	0.077	14.696
Southern_Wind_Farms	128	4	15	25	5.472	2.097	0.077	14.696
NEPC_3	126	4	15	25	5.279	2.083	0.069	16.090
NEPC_2	125	4	17	25	5.472	2.097	0.058	19.360

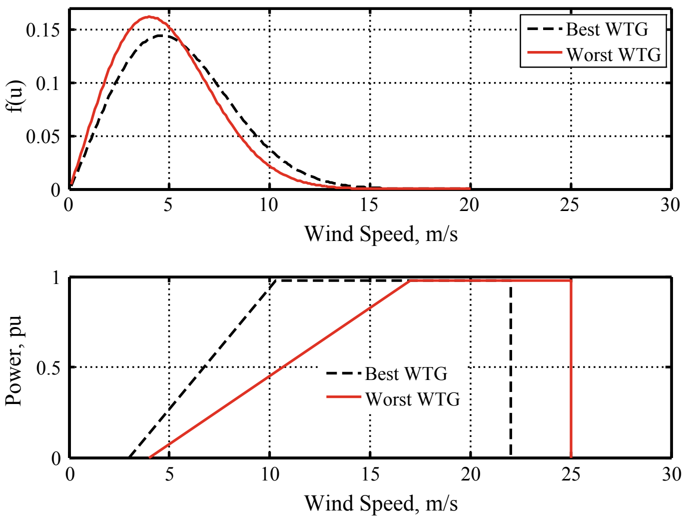


Fig. 22 Comparison between the best and worst WT types for the Douhlom site

site (WT #125). The first curve shows the speed distribution facing each WT in the Douhlom site. The second curve shows the generated power against wind speed for WT #2 and WT #125. It is clear from this figure that most of the speed distribution for Douhlom is lying within the generated area of WT #2. But, most of the speeds are shown below the cut-in speed of WT #125 and there is no considerable speed over the rated speed of WT #125. The same results can be concluded from the next two figures, Fig. 23 and Fig. 24, which show the distribution of wind speed and the power characteristics against wind speed for the best and worst five WT types in the Douhlom site, respectively. These two figures show that most of the speed in the Douhlom site is lying within the generated power of the five best WT types but most of the speeds are not lying within the generated power area of the worst five WT types in Douhlom site.

Tables 7 and 8 show the list of the best 10 WTs and the worst 10 WTs for the Douhlom site. These tables also show the WT names, numbers, specifications, Weibull parameters, capacity factor, and cost of generated energy with each WT type.

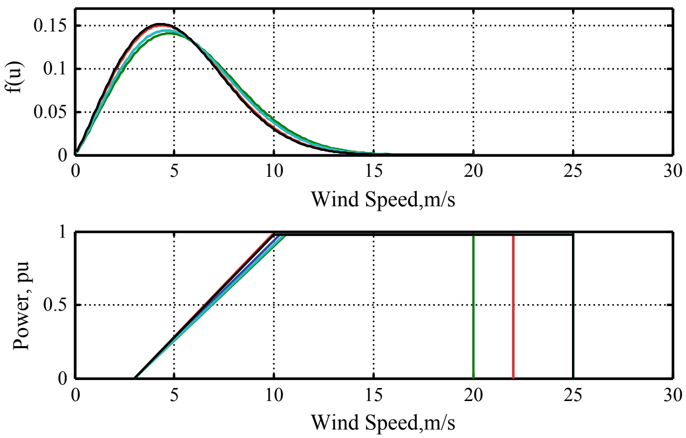


Fig. 23 Best five WT types in the Douhlom site

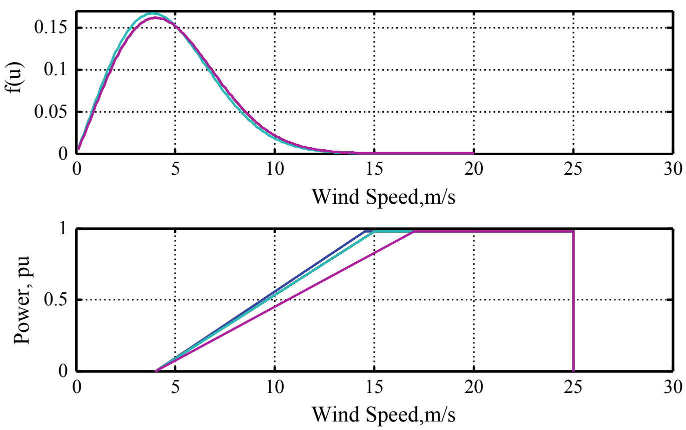


Fig. 24 Worst five WT types for Douhlom

Moreover, the prices of energy generated are inversely proportional to the capacity factor in each case. Also, it is better to use WT #2 in the Douhlom site for the minimum cost of generated energy. Also if a wrong WT type like WT #125 is used instead of WT #2 in Douhlom, the price of the generated kWh will be more than four times the price associated with WT #2. So it is not recommended to use any one of the worst WT types shown in Table 8 in the Douhlom site.

4.1.3 Detailed Results from Guriat Site

It is clear from the results of the new proposed computer program that has been summarized in Table 9 and Table 10 that the Guriat site is the third best site for wind energy applications. The best WT type for the Guriat site is WT #2. The price of kWh generated from Guriat with WT #2 is 4.396 Cents/kWh. The worst WT that can be used in Guriat is NEPC_2 (WT #125) with 18.708 Cents/kWh which is clear that it is four times the price of kWh generated in Guriat with WT #2. The main reason of the big difference in the price of kWh is because most of the available wind speed of the Guriat site is used to generate power from WT #2 but most of these speeds are not used to generate power from WT #125. These conclusions are shown very clear in Fig. 25. This figure shows a comparison between the best WT for Guriat (WT #2) and the worst WT for this site (WT #125). The first curve shows the speed distribution facing each WT in the Guriat site. The second curve shows the generated power against wind speed for WT #2 and WT #125. It is clear from

Table 9 The detailed results for the best 10 WT types for the Guriat site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	#							
Goldwind_3	2	3	10.3	22	6.121	1.959	0.284	4.396
Acciona_6	1	3	10.6	20	6.201	1.931	0.281	4.456
Goldwind_4	3	3	9.9	22	5.782	2.066	0.261	4.577
HZ_WindPR_3	113	3	10.5	25	6.121	1.959	0.275	4.577
Envision_4	54	3	10	25	5.779	2.067	0.256	4.757
Envision_3	53	3	10.5	25	5.864	2.016	0.246	4.817
Acciona_3	17	3	10.5	20	5.864	2.016	0.246	4.938
Acciona_5	19	3.5	11	25	6.201	1.931	0.249	4.938
Goldwind_2	88	3	11	22	6.121	1.959	0.254	4.938
Guodian_1	97	3	10.5	25	5.864	2.016	0.246	4.938

Table 10 The detailed results for the worst 10 WT types in Guriat site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	#							
GC_China_Turbine_Corp_1	74	4	15	25	5.779	2.067	0.093	12.686
GC_China_Turbine_Corp_2	75	4	15	25	5.779	2.067	0.093	12.686
GC_China_Turbine_Corp_3	76	4	15	21	5.779	2.067	0.093	12.686
Gamesa_2	68	4	15	25	5.779	2.067	0.093	13.089
Gamesa_3	69	4	15	25	5.779	2.067	0.093	13.104
Ecotecnia_2	44	4	14.5	25	5.343	1.948	0.088	13.441
NEPC_1	124	4	15	25	5.343	1.948	0.082	14.416
Southern_Wind_Farms	128	4	15	25	5.343	1.948	0.082	14.416
NEPC_3	126	4	15	25	5.145	2.012	0.068	16.379
NEPC_2	125	4	17	25	5.343	1.948	0.063	18.708

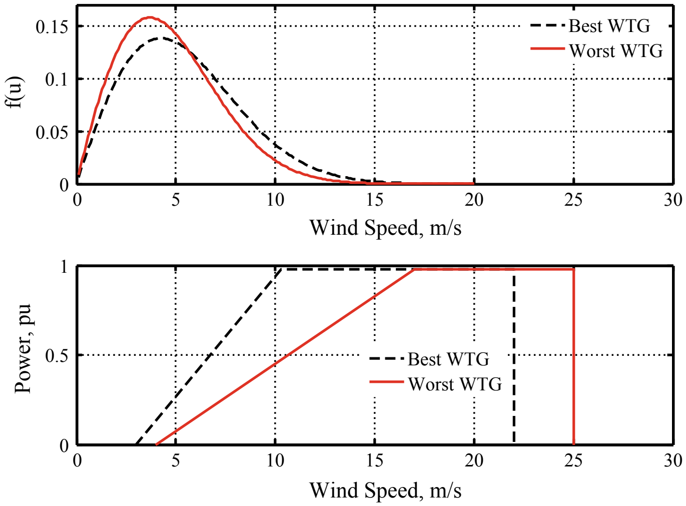


Fig. 25 Comparison between the best and worst WT types for the Guriat site

this figure that most of the speed distribution for Guriat is lying within the generated area of WT #2. But, most of the speeds are shown below the cut-in speed of WT #125 and there is no considerable speed over the rated speed of WT #125. The same results can be concluded from the next two figures where Fig. 26 and Fig. 27 show the distribution of wind speed and the power characteristics against wind speed for the best and worst five WTs in the Guriat site, respectively. These two figures show that most of the speeds in the Guriat site are lying within the generated power of five

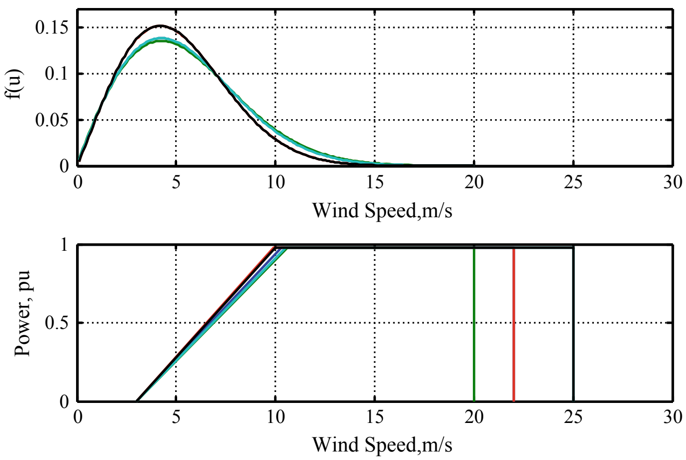


Fig. 26 Best five WT types in the Guriat site

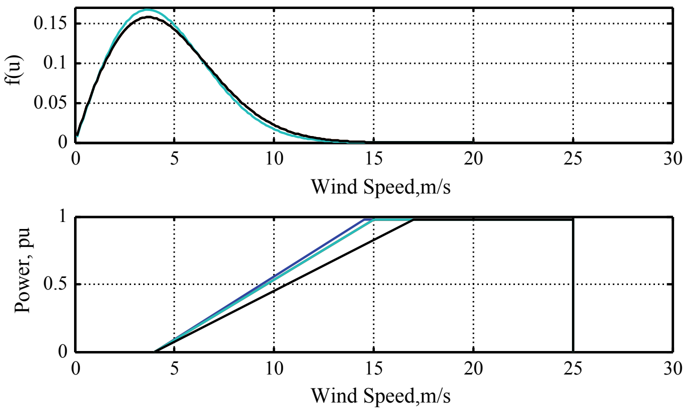


Fig. 27 Worst five WT types for the Guriat site

best WT types but most of the speeds are not lying within the generated power area of the worst five WT types in the Guriat site.

Tables 9 and 10 show the list of the best 10 WTs and the worst 10 WTs for the Guriat site. These tables also show the WT names, numbers, specifications, Weibull parameters, capacity factor, and the price of kWh generated with each WT type. It is also clear from these two tables that the prices of kWh generated are inversely proportional to the capacity factor in each case. Also, it is recommended to use WT #2 in the Guriat site for the minimum price of kWh generated. Also if a wrong WT type like WT #125 is used instead of WT #2 in Guriat the price of the generated kWh will be almost four times the price associated with WT #2. So it is not recommended to use any one of the worst WTs shown in Table 10 in the Guriat site.

4.1.4 Detailed Results from Hail Site

It is clear from the results of the new proposed computer program that has been summarized in Tables 11 and 12 that the Hail site is the fourth best site for wind energy applications. The best WT type for the Hail site is WT #1. The price of kWh

Table 11 The detailed results for the best 10 WT types in the Hail site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	**#**							
Acciona_6	1	3	10.6	20	5.357	1.429	0.258	4.577
Goldwind_3	2	3	10.3	22	5.338	1.434	0.267	4.577
HZ_WindPR_3	113	3	10.5	25	5.338	1.434	0.261	4.657
Goldwind_4	3	3	9.9	22	5.096	1.518	0.251	4.697
Envision_4	54	3	10	25	5.094	1.519	0.247	4.878
Envision_3	53	3	10.5	25	5.111	1.515	0.233	4.938
Goldwind_2	88	3	11	22	5.338	1.434	0.245	4.938
Acciona_3	17	3	10.5	20	5.109	1.515	0.232	4.998
Guodian_3	99	3	10.5	25	5.109	1.515	0.233	4.998
Fuhrlander_4	63	3.5	11.5	25	5.782	1.497	0.242	5.018

Table 12 The detailed results for the worst 10 WT types in the Hail site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	#							
GC_China_Turbine_Corp_3	76	4	15	21	5.094	1.519	0.111	10.157
Gamesa_3	69	4	15	25	5.093	1.519	0.111	10.408
Gamesa_2	68	4	15	25	5.093	1.519	0.111	10.413
W.T.S._4,	7	7.1	16.2	27	6.415	1.379	0.118	10.598
Ecotecnia_3	45	4	14.5	25	4.778	1.566	0.094	10.598
Ecotecnia_2	44	4	14.5	25	4.743	1.577	0.091	11.393
NEPC_1	124	4	15	25	4.743	1.577	0.086	12.059
Southern_Wind_Farms	128	4	15	25	4.743	1.577	0.086	12.059
NEPC_3	126	4	15	25	4.614	1.634	0.074	13.312
NEPC_2	125	4	17	25	4.743	1.577	0.069	14.914

generated from Hail with WT #1 is 4.577 Cents/kWh. The worst WT type that can be used in Hail is NEPC_2 (WT #125) with 14.914 Cents/kWh which is clear that it is more than three times the price of kWh generated in Hail with WT #1. The main reason of the big difference in the price of kWh is because most of the available wind speed of the Hail site is used to generate power from WT #1 but most of these speeds are not used to generate power from WT #125. These conclusions are shown very clear in Fig. 28. This figure shows a comparison between the best WT type for Hail (WT #1) and the worst WT type for this site (WT #125).

The first curve shows the speed distribution facing each WT type in the Hail site. The second curve shows the generated power against wind speed for WT #1 and WT #125. It is clear from this figure that most of the speed distribution for Hail is lying within the generated area of WT #1. But most of the speeds are shown below the cut-in wind speed of WT #125 and there is no considerable speed over the rated speed of WT #125. The same results can be concluded from the next two figures where Fig. 29 and Fig. 30 show the distribution of wind speed and the power characteristics

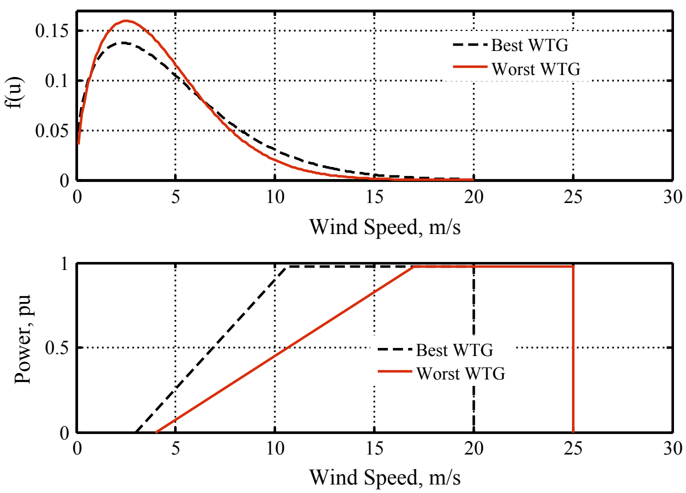


Fig. 28 Comparison between the best and worst WT types for the Hail site

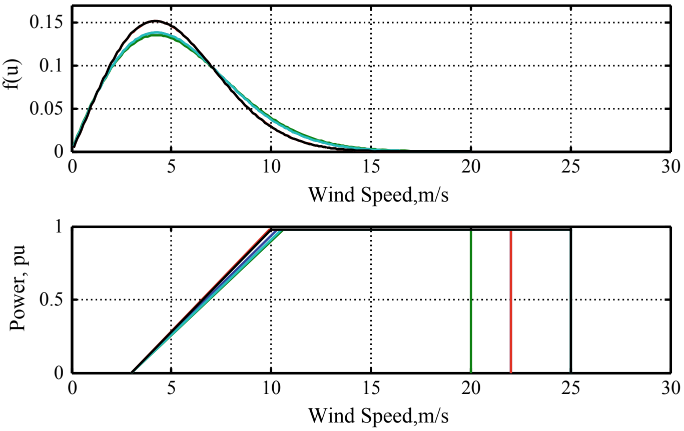


Fig. 29 Best five WT types in the Hail site

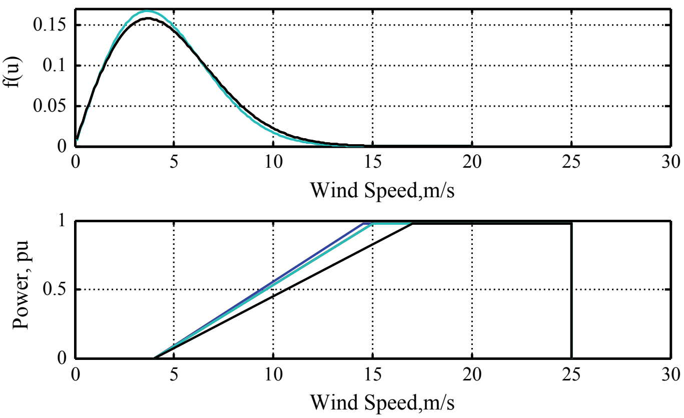


Fig. 30 Worst five WT types in the Hail site

against wind speed for the best and worst five WT types in the Hail site respectively. These two figures show that most of the speed in the Hail site is lying within the generated power of five best WTs but most of the speeds are not lying within the generated power area of the worst five WTs in the Hail site.

Tables 11 and 12 show the list of the best 10 WT types and the worst 10 WT types for the Hail site. These tables also show the WT names, numbers, specifications, Weibull parameters, capacity factor, and the cost of generated energy from each WT type. Moreover, the cost of generated energy is inversely proportional to the capacity factor in each case. Also, it is better to use WT #1 in the Hail site for the minimum price of kWh generated. Also if a wrong WT type like WT #125 is used instead of WT #1 in Hail the cost generated energy will be almost three times the cost associated

Table 13 The detailed results for the best 10 WT types in the Skaka site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	#							
Goldwind_3	2	3	10.3	22	5.309	1.690	0.237	5.239
Acciona_6	1	3	10.6	20	5.369	1.662	0.235	5.299
HZ_WindPR_3	113	3	10.5	25	5.309	1.690	0.230	5.380
Goldwind_4	3	3	9.9	22	5.086	1.768	0.223	5.420
Envision_4	54	3	10	25	5.081	1.769	0.219	5.600
Envision_3	53	3	10.5	25	5.116	1.754	0.206	5.721
Acciona_3	17	3	10.5	20	5.114	1.754	0.206	5.781
Goldwind_2	88	3	11	22	5.309	1.690	0.214	5.781
Guodian_1	97	3	10.5	25	5.114	1.754	0.206	5.781
Guodian_3	99	3	10.5	25	5.114	1.754	0.206	5.781

Table 14 The detailed results for the worst 10 WT types in the Skaka site

WT		u_c	u_r	u_f	c	k	C_F	ECF
Name	#							
GC_China_Turbine_Corp_2	75	4	15	25	5.081	1.769	0.084	12.726
GC_China_Turbine_Corp_3	76	4	15	21	5.081	1.769	0.084	12.766
Ecotecnia_2	44	4	14.5	25	4.627	1.510	0.092	12.790
Gamesa_3	69	4	15	25	5.080	1.770	0.084	13.069
Gamesa_2	68	4	15	25	5.080	1.770	0.084	13.089
W.T.S._4,	7	7.1	16.2	27	6.465	1.752	0.079	13.328
NEPC_1	124	4	15	25	4.627	1.510	0.087	13.522
Southern_Wind_Farms	128	4	15	25	4.627	1.510	0.087	13.522
NEPC_3	126	4	15	25	4.428	1.581	0.071	15.127
NEPC_2	125	4	17	25	4.627	1.510	0.071	16.650

with WT #1. So it is not recommended to use any one of the worst WT types shown in Table 12 in the Hail site.

4.1.5 Detailed Results from Skaka Site

It is clear from the results of the new proposed computer program that has been summarized in Tables 13 and 14 that the Skaka site is the fifth best site for wind energy applications. The best WT type for the Skaka site is WT #2. The price of kWh generated from Skaka with WT #2 is 5.239 Cents/kWh. The worst WT type that can be used in Skaka is NEPC_2 (WT #125) with 16.65 Cents/kWh which is clear that it is three times the price of kWh generated in Skaka with WT #2. The main reason of the big difference in the price of kWh is because most of the available wind speed of the Skaka site is used to generate power from WT #2 but most of these speeds are not used to generate power from WT #125. These conclusions are shown very clear in Fig. 31. This figure shows a comparison between the best WT type for Skaka (WT #2) and the worst WT type for this site (WT #125). The first curve shows the speed distribution facing each WT type in the Skaka site. The second curve shows the generated power against wind speed for WT #2 and WT #125. It is clear from this figure that most of the speed distribution for Skaka is lying within the generated area of WT #2. But, most of the speeds are shown below the cut-in wind speed of WT #125 and there is no considerable speed over the rated speed of WT #125. The same results can be concluded from the next two figures where Fig. 32 and Fig. 33 show

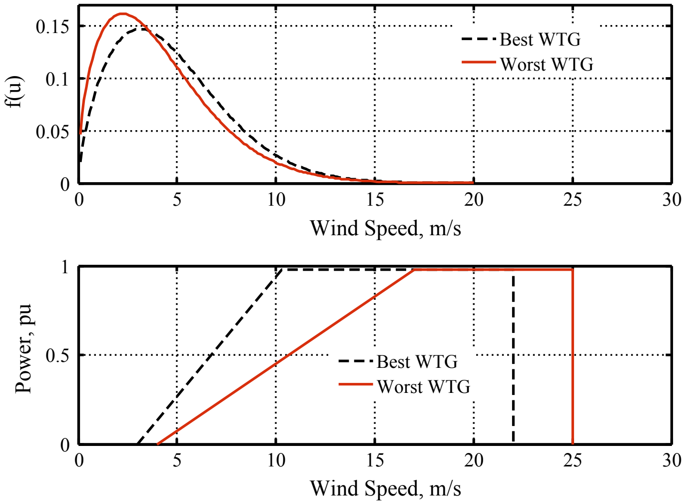


Fig. 31 Comparison between the best and worst WT types for the Skaka site

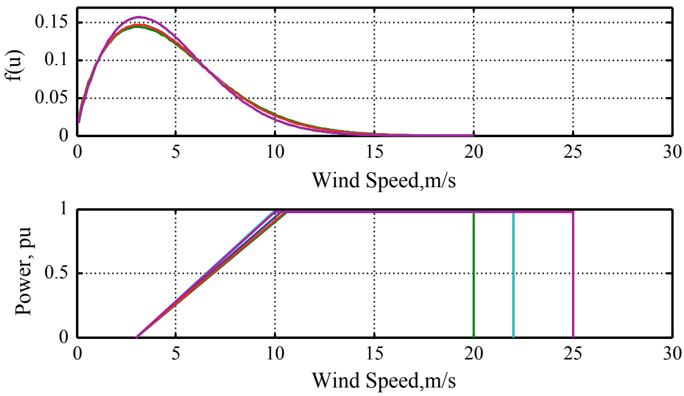


Fig. 32 Best five WT types in the Skaka site

the distribution of wind speed and the power characteristics against wind speed for the best and worst five WT types in the Skaka site, respectively. These two figures show that most of the speed in the Skaka site is lying within the generated power of the five best WTs but most of the speeds are not lying within the generated power area of the worst five WT types in the Skaka site.

Tables 13 and 14 show the list of the best 10 WT types and the worst 10 WT types for the Skaka site. These tables also show the WT names, numbers, specifications, Weibull parameters, capacity factor, and the cost of generated energy from each WT type. The prices of generated energy is inversely proportional to the capacity factor in each case. Also, it is better to use WT #2 in the Skaka site for the minimum cost of the generated energy. Also if a wrong WT type like WT #125 is used instead of WT #2 in Skaka the cost of the generated energy is almost three times the cost associated

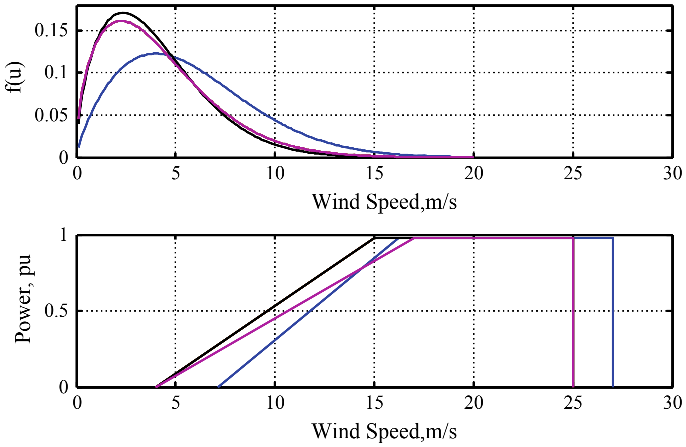


Fig. 33 Worst five WT types in the Skaka site

with WT #2. So it is not recommended to use any one of the worst WT types shown in Table 14 in the Skaka site.

5 Conclusions

The cost of energy generated from wind energy systems, WES, is depending on the sites that will be used to install the WES and the wind turbine (WT) used in this site. The WT can work with high performance in some sites but it may not work well in some other sites, and for this reason, it is essential to start selecting the best site among several sites available to install the WES and the suitable WT for this site. For this reason, the new proposed computer program is used to handle this optimization problem. 32 sites are selected in different provinces of Saudi Arabia and 140 market available WT types are selected to choose the best site and the best WT suitable for this site. The best site among these sites is the Dammam and the best WT suitable for this site is Goldwind_3. The cost of energy for this option is 4.16 Cents/kWh. Also, it is clear from the results of the proposed computer program the worst site among these sites understudy is the Makkah site where the cost of energy is 129.81 Cents/kWh when using the *AWE_1* WT. The big difference between the cost of energy improved the superiority to be used to choose the best site and the best WT.

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