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Comparative study between measured and estimated wind energy yield

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Abstract: This paper proposes a power-speed (P-V) model of the wind turbine by assuming three different functions for the first performance region; cubic, quadratic and uncorrected cubic. These three functions have been compared with the manufacturer models of five different wind turbines which were installed in five different locations in Jordan; Tafila, Hofa, Fujeij, Al Rajef, and Deahan. The wind turbine of these wind farms are considered as large scale HAWT in the range of Mw. The generated P-V models are developed by applying a new method described in this paper which is basically based on generating a multiplier factor x. In this study, the quadratic model shows the highest correlation compared with the other models. The wind energy yield for the selected wind farms has been estimated by a mathematical modelling based on Rayleigh distribution function, derived in this paper. The energy yield using this mathematical model has been compared with the measured energy output of four wind farms, Tafila, Hofa, Al Rajef, and Deahan. The measured energy were provided by the operators of these wind farms which are: Jordan Wind Project Company(JWPC), Central Electricity Generation Company (CEGC), Green Watts Renewable Energy (GWRC)and Korean Southern Power Company(KOSPO). Results show that the estimated energy using the quadratic wind turbine model for all wind farms are very close to the actual output. Accuracy analysis for the quadratic model resulted in an error of less than 10% between the measured and estimated energy output for all wind farms. The capacity factors for the selected wind farms have been estimated using the quadratic P-V model. Results show that Tafila wind farm has the highest capacity factor which is around 47%.

Key words: Wind energy, wind turbine, Rayleigh approach, energy density, power-speed curve

1. Introduction

Wind energy is the most rapid growing renewable energy technology. Estimating the P-V characteristics of the wind turbines is essential in the preliminary assessment of their energy yield. The typical representation of the P-V characteristic of the wind turbine consists of two main performance regions, see Figure 1. The output power of the wind turbine, corresponding to the first performance region, is affected by the cut-in wind speed (V_I) and rated wind speed (V_R). Further, the output of the second performance region is equal to the rated wind turbine power (P_R).

Several studies have been investigated to give an accurate mathematical modelling for the first performance region of the P-V characteristic [1–4]. Shoaib et al. in [5], suggested a cubic polynomial function to fit the first performance region, then extracted wind energy on a seasonal and annual basis has been evaluated for selected wind turbines using the suggested model. In [6], Wang et al. suggested six P-V characteristics to

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represent the behavior of several types of real wind turbines in China. Both [5, 6] did not provide comparisons with the manufacturer P-V models in their work for validation purposes. Albadi and El-Saadany in their letter in [7], provided a complete derivation for the capacity factor of a given wind turbine based on a cubic wind turbine model. Then, a comparison between the manufacturer model and the cubic model is provided in this letter. However, they did not provide a comparison with other turbine models such as linear or quadratic models. In [8], Mathew et al. developed new performance criteria, named as normalized energy, which was used to compare the performance characteristics for wind turbines of different ratings.

The research study in this paper takes several wind turbines in Jordan as research objects to review and compare the generated P-V characteristics with the manufacturer models. The main contribution and investigation of this paper compared with other studies can be summarized here. This paper provides a new method for generating the P-V characteristics of the wind turbine models using three different functions (cubic, quadratic and uncorrected cubic). The proposed method was validated using five actual wind farms (Tafila, Hofa, Fujeij, Al Rajef, and Deahan wind farms). The study has concluded that the quadratic behavior of the wind turbine model is very close to the manufacturer models. In addition, a novel model is derived for estimating the extracted energy of the wind turbine using Weibull and Rayleigh distribution approach. The estimated energy output of the wind turbines using these functions was compared with the measured output for each wind farm. The study has shown that using the quadratic model, the predicted energy is more realistic than the cubic model adopted in several studies in the literature [9, 10].

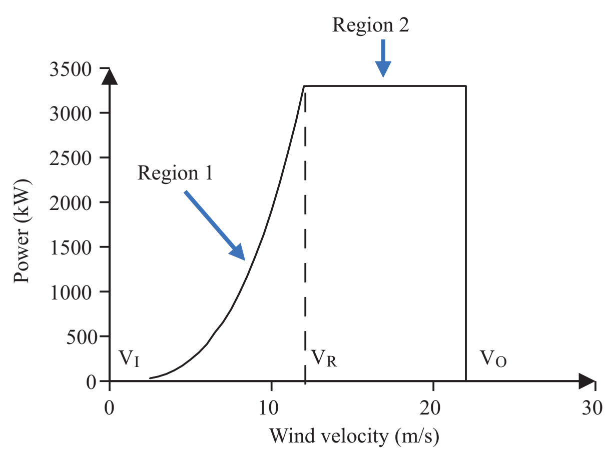

Figure 1. Power curve for a typical wind turbine.

2. Evolution of wind energy in Jordan

The first wind farm in Jordan was established in 1988 in Al-Ibrahimia city. It consists of four wind turbines with a total production capacity of 320 kw. The second wind farm was established in 1996 in Hofa, north of Jordan. It consists of five wind turbines with a total production capacity of 1.125 Mw. Two wind farms are recently established. The first one in Tafila province which consists of 38 turbines with 3.075 Mw each and a total capacity of 117 Mw. The second wind farm in Ma'an which consists of seven turbines with two Mw each and a total production capacity of 14 Mw.

Figure 2 shows the evolution of wind energy production capacity in Jordan. By 2017, the energy production of the operated wind farms reached 132 Mw. Approximately, 155 Mw wind farms are under construction and expected to be integrated to the grid in the near future [11]. Table 1 shows more details about the operated and the under construction wind farms in Jordan in the period between 1988 and 2107.

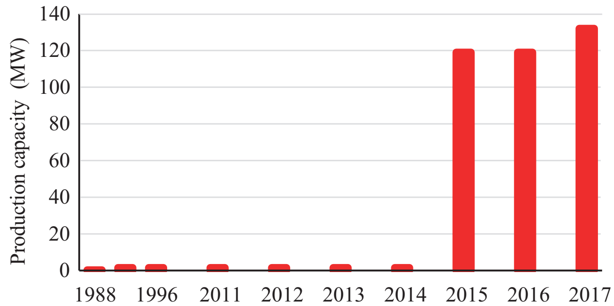

Figure 2. The evolution of the wind production capacity in Jordan.

Table 1. Distribution of wind farms in Jordan.

Project	**Number of turbines**	**Turbine model**	**Turbine rated power(kw)**	$V_I(m/s)$	$V_R(m/s)$	$V_o(m/s)$	**Hub height(m)**	**Total capacity(Mw)**
Tafila	38	Vestas V112/3075	3075	2.5	13	25	84	116.85
Hofa	5	Vestas V27/225	2250	3.5	14	22	33.5	1.125
Fujeij	27	Gamesa G126/3300	3300	2.5	12	25	117	89.1
Al Rajef	41	Gamesa G114/2000	2000	3	11	25	80	86.1
Daehan	15	Vestas V136/3450	3450	2.5	11	22	149	51.75

3. Analysis of wind regime

Wind power refers to the process of generating electricity using wind turbines. Mathematically, the wind power, P_w, is given by[11]:

$$P_w = \frac{1}{2}\rho A v^3, \tag{1}$$

where A is the swept area in m^2, ρ is the air density in kg/m^3 and v is wind velocity in m/s. Eq. 1 shows that the wind power depends on the air density, rotor area and the wind speed. Since the wind power is a cubic function of the wind speed, a small difference in the estimated wind speed leads to a large variation in the assessment of the wind energy in a specific wind site.

Assessment of wind energy potential is significantly affected by the distribution of the wind speed, which can be described using several density functions. Each function can be characterized by two main functions: the probability density function $f(v)$ and the cumulative distribution function F(v). $f(v)$ indicates the fraction of time in which the wind is at a given velocity. F(v) is obtained by a numerical integration of $f(v)$. It provides the probability for an interval of wind speeds in a specific wind distribution.

Weibull distribution is one of the most accurate distribution functions which requires wind speed data of the studied location in order to estimate scale and shape factors. The accuracy of Weibull scale and shape factors depends on the resolution of the available measured wind speed data [12]. The probability density function of

Weibull distribution, $f_w(v)$, is given by Eq. 2 [13, 14]:

$$f_w(v) = \frac{k}{c}(\frac{v}{c})^{k-1} e^{(\frac{v}{c})^k}, \tag{2}$$

where k and c are the Weibull shape and scale factors respectively. Integrating Eq. 2, the cumulative distribution of the Weibull function, $F_w(v)$, is given by:

$$F_w(v) = 1 - e^{-(\frac{v}{c})^k}. \tag{3}$$

Rayleigh distribution function is a particular case of Weibull distribution, which gives an approximate estimation of the wind speed by taking $k = 2$. Therefore, the scale factor-based on Rayleigh approach can be evaluated by:

$$c = \frac{2V_m}{\sqrt{\pi}}, \tag{4}$$

where V_m is the average wind speed. By substituting Eq. 4 in Eq. 2 at $k = 2$, the probability density function-based on Rayleigh approach, $f_R(V)$, can be evaluated by:

$$f_R(v) = \frac{\pi}{2}(\frac{v}{V_m^2}) e^{-\frac{\pi}{4}(\frac{v}{V_m})^2}. \tag{5}$$

Similar to the Weibull approach, the corresponding cumulative distribution function-based on Rayleigh approach, $F_R(V)$, is given by:

$$F_R(v) = 1 - e^{-\frac{\pi}{4}(\frac{v}{V_m})^2}. \tag{6}$$

4. Derivation of energy generated by the wind turbine

As mentioned in section 1, the typical model of the wind turbine consists of two main performance regions. The output power of the wind turbine in both performance regions is given by [8, 15–17]:

$$P_V = \begin{cases} P_R\left(\frac{v^n - V_I^n}{V_R^n - V_I^n}\right) & V_I < V < V_R \\ P_R & V_R < V < V_o \end{cases} \tag{7}$$

where n is the power-speed proportionality factor and V_o is the cut out wind speed of the wind turbine. The energy produced by region 1 and region 2 for any distribution function is given by E_{IR} and E_{RO}, respectively:

$$E_{IR} = T\int_{V_I}^{V_R} P_V f(v) dv, \tag{8}$$

$$E_{RO} = T\int_{V_R}^{V_O} f(v) dv, \tag{9}$$

where T is the operating time of the wind turbine in both performance regions measured in hours. In case of the Weibull distribution, the energy produced by the wind turbine in the first performance region is given by (E_{IR_w}):

$$E_{IR_w} = T\int_{V_I}^{V_R} P_v f_w(v). \tag{10}$$

Substitute Eqs. 2 and 7 in Eq. 10, rearrange and simplify the equation, yields:

$$E_{IR_w} = \frac{P_R T c^n}{V_R^n - V_I^n} \int_{X_I}^{X_R} X^{\frac{n}{k}} e^{-X} dX - \frac{P_R T V_I^n}{V_R^n - V_I^n} (e^{-X_I} - e^{-X_R}), \tag{11}$$

where

$$X_I = (\frac{V_I}{c})^k, X_R = (\frac{V_R}{c})^k, X_O = (\frac{V_O}{c})^k. \tag{12}$$

In the second performance region, the energy developed by the wind turbine using Weibull distribution approach, E_{RO_w}, is given by:

$$E_{RO_w} = T P_R \int_{V_R}^{V_O} f_w(v) dv. \tag{13}$$

Substitute Eq. 2 in Eq. 13 and simplify the equation, yields:

$$E_{RO_w} = P_R T (e^{-X_R} - e^{-X_O}). \tag{14}$$

The total energy produced by the turbine using Weibull distribution approach, E_w, is the sum of the energy in both performance regions:

$$E_w = E_{IR_w} + E_{RO_w}. \tag{15}$$

Similar to the Weibull approach, the energy generated by the first performance region of the wind turbine based on Rayleigh approach is given by (E_{IR_R}):

$$E_{IR_R} = T \int_{V_I}^{V_R} P_v f_R(v) \tag{16}$$

$$E_{IR_R} = \frac{2^n P_R T}{\pi^{\frac{n}{2}} (V_R^n - V_I^n)} \int_{X_I}^{X_R} X^{\frac{n}{k}} e^{-X} dX - \frac{P_R T V_I^n}{V_R^n - V_I^n} (e^{-X_I} - e^{-X_R}), \tag{17}$$

where

$$X_I = \frac{\pi}{4} (\frac{V_I}{V_m})^2, X_R = \frac{\pi}{4} (\frac{V_R}{V_m})^2, X_O = \frac{\pi}{4} (\frac{V_O}{V_m})^2. \tag{18}$$

In the second performance region, the energy generated by the wind turbine using Rayleigh distribution approach, E_{RO_R}, is given by:

$$E_{RO_R} = P_R T (e^{-X_R} - e^{-X_O}). \tag{19}$$

The total energy produced by the turbine using a Rayleigh distribution approach, E_R,is the sum of the energy in both performance regions:

$$E_R = E_{IR_R} + E_{RO_R}. \tag{20}$$

5. Comparison of the estimated power curve models

P-V curves of the wind turbines are used to estimate their extracted energy. However, the prediction of the wind turbine energy in the first performance region is difficult due to the difficulty in determining the actual relation between the turbine power and the wind speed, see coefficient (n) in Eq. 7. This coefficient has to be appropriately selected to obtain a good correlation between the wind turbine analytical model and the one provided by the manufacturer. Several suggested studies indicate that the most suitable value for this coefficient is three [9, 10]. Their assumption was based on the cubic relation between the wind power and the wind speed which has to be reflected in the turbine model, see Eq. 1.

Practically, several factors affect the n-coefficient. Some of these factors are based on the type of the wind turbine [8, 18]. Others are based on the aerodynamic behaviour of the wind turbines [18, 19]. The study in this paper aims to generate P-V characteristics for several real wind turbines installed in different wind farms in Jordan. These wind farms are: Tafila, Hofa, Fujeij, Al Rajef, and Daehan. The generated P-V characteristics are developed by assuming three different functions for the relation between the turbine power and the wind speed. The first function is the normal cubic function, which is denoted in this paper, as uncorrected cubic function. The other two functions are quadratic and cubic functions with n = 2 and 3, respectively. The last two functions are obtained by multiplying the power in the first performance region of Eq. 7 by a multiplier factor called x, where $x = P_R/V_R^n$. Table 2 shows the multiplier factors for the quadratic and the cubic functions. The estimated P-V characteristics using these three functions are compared with the manufacturer models for all wind farms.

Table 2. Distribution of wind farms in Jordan.

Wind farm	Quadratic multiplier ($x_{Quadratic}$)	Cubic multiplier(x_{Cubic})
Tafila	18.19	1.39
Hofa	11.48	0.82
Fujeij	22.92	1.91
Al Rajef	16.52	1.5
Daehan	28.51	2.59

In Tafila wind site where Vestas V112/3075 wind turbines are installed, the estimated P-V characteristics using the previous functions compared with the manufacturer model are shown in Figure 3. It is obvious that the quadratic P-V characteristic is the closest characteristic to the manufacturer model. Moreover the uncorrected cubic function is less accurate than the corrected one. In the second performance region of the P-V characteristics, the rated power is obtained using all functions.

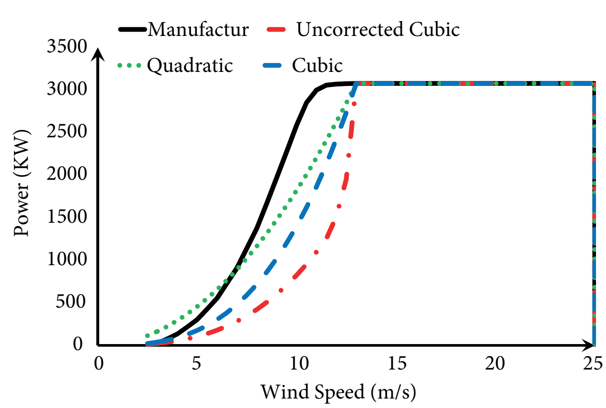

Figure 3. Cubic, quadratic, uncorrected cubic and manufacturer for Vestas V112/3075 wind turbine installed in Tafila, Jordan.

Similarly, the P-V characteristics for Vestas V27/225 and Gamesa G126/3300 wind turbines, which are installed in Hofa and Fujeij wind farms respectively, are generated based on the previous functions. Comparisons between the estimated characteristics and the manufacturer models for both wind turbines are shown in Figures 4 and 5, respectively. It is also clear that the quadratic P-V characteristics are the closest to the manufacturer models for both wind turbines. In Al Rajef and Daehan wind farms, where Gamesa G114/2000 and Vestas V136/3450 are installed respectively, the quadratic functions of the P-V characteristics have also provided the highest correlation with the manufacturer models for both wind turbines, see Figures 6 and 7.
It is worth to conclude that the behaviour of the P-V characteristics for a 3-blades HAWT in the first performance region is close to the quadratic behaviour with n = 2. This refutes the common saying that the relationship between wind velocity and energy generated by the wind turbines is very close to the cubic relation.

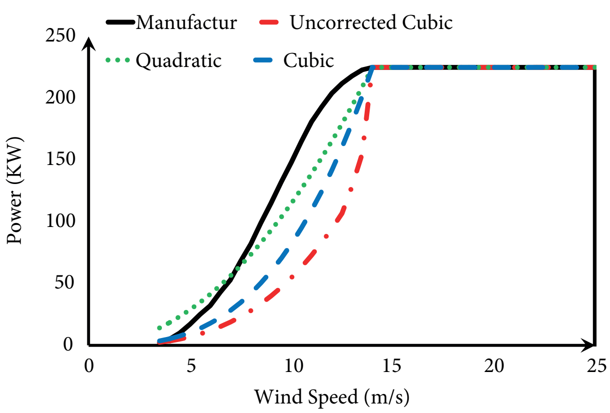

Figure 4. Cubic, quadratic, uncorrected cubic and manufacturer for Vestas V27/225 wind turbine installed in Hofa, Jordan.

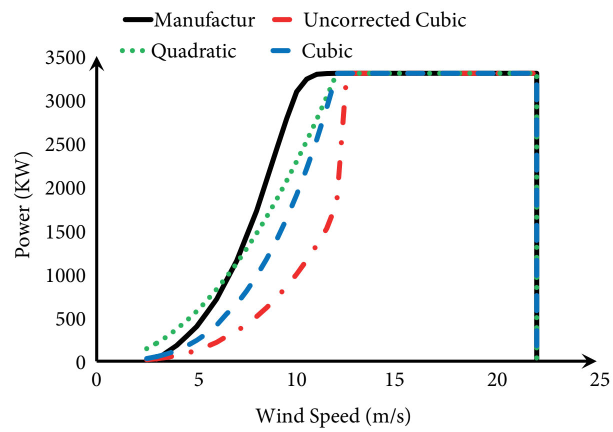

Figure 5. Cubic, quadratic, uncorrected cubic and manufacturer for Gamesa G126/3300 wind turbine installed in Fujeij, Jordan.

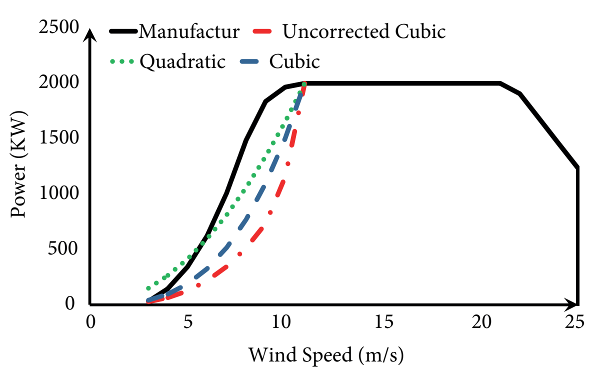

Figure 6. Cubic, quadratic, uncorrected cubic and manufacturer for Gamesa G114/2000 wind turbine installed in Al Rajef, Jordan.

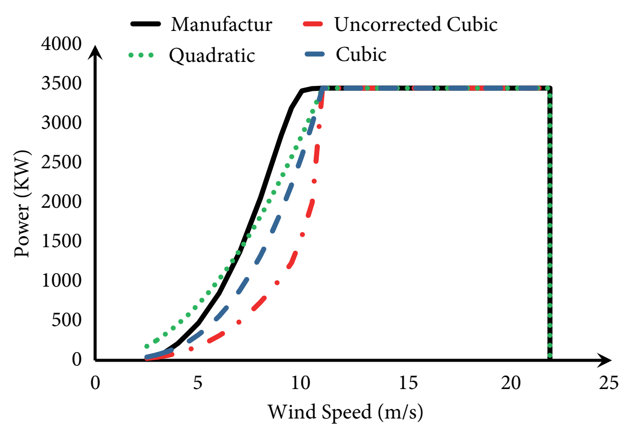

Figure 7. Cubic, quadratic, uncorrected cubic and manufacturer for Vestas V136/3450 wind turbine located in Daehan.

6. Corrected wind speed data at different height

For winds near the ground surface, frictional effects play a significant role in wind speed. Ground obstructions retard the movement of air close to the ground surface, causing a reduction of wind speed. Several methods are used to correct the wind speed for different height [18–24]. Logarithm law, which is used in many research work in the literature [18, 19], is an empirical formula in which the mean wind speed at a given height using this law can be evaluated as follows:

$$V(Z_R) = V(Z)\frac{ln(\frac{Z_R}{Z_0})}{ln(\frac{Z}{Z_0})}, \tag{21}$$

where $V(Z_R)$ is the wind speed at a height of Z_R which is usually considered as the hub height of the wind turbine. $V(Z)$ is the wind speed measured in the meteorological station which is usually 10 m height, and Z_0 is the roughness height which depends on the terrain description as listed in Table 3.

Table 3. Values of Z_0 at different terrain description [25].

Terrain description	$Z_0(m)$
Open flat terrain, grass, few isolated obstacles	0.05
Low crops, occasional large obstacles	0.10
parkland, bushes, numerous obstacles	0.5
Regular large obstacle coverage (suburb, forest)	1.0
City centre with high and low rise buildings	$\geqslant 2$

7. Error analysis

7.1. Estimated vs. measured energy output of wind farms

Jordanian National Energy Research Centre offered the average wind speeds for the selected wind farms on a monthly basis. Table 4 shows the monthly average wind speed at the hub height for all wind farms. The extracted energy for four wind farms, Tafila, Hofa, Al Rajef, and Daehan, are measured and provided by their operators, see Table 5.

This section provides a comparison between the measured energy output of Hofa wind farm with the estimated values using the three different functions of the P-V characteristics. Since the average wind speed is the only available wind data, the estimated energy output has been evaluated based on Rayleigh distribution function. Table 6 shows a comparison between the measured energy output of the selected wind farms with the estimated values using cubic, quadratic and uncorrected cubic functions. It is clear from Table 6 that the estimated energy output using the quadratic scenarios is very close to the measured values in all cases. Percentage error calculations between the estimated and the measured values are shown in Table 7. The error analysis has been done based on the following definition:

$$Error = \left|\frac{E_{T_{measured}} - E_{T_{estimated}}}{E_{T_{measured}}}\right| \times 100\%, \tag{22}$$

where $E_{T_{estimated}}$ is the total energy estimated using different scenarios, and $E_{T_{measured}}$ is the total energy measured by the operator.

The accuracy of the energy production using the quadratic model has shown better and acceptable energy estimation compared to the traditional cubic model. The error in energy estimation ranges from a minimum value of 1.29% in the month of December for Tafilah wind farm to a maximum value of 9.81% in the month of February of Hofa wind farm, compared to the cubic model which varies between a minimum value of 2.67% in the month of January of Daehan wind farm and a maximum value of 45.92% in the month of November of Hofa wind farm. Definitely, this demonstrates that the quadratic model is the best to be used for those turbines installed in Jordan. Furthermore, the model can also be used for:

1. The validated model can be utilized routinely for the assessment of wind energy potential of different future and existing wind sites.
2. A decision can be made whether a wind farm can be built or not in a specific wind site, without even a need to install anemometers.
3. Evaluating the capacity factor of the wind farm, as will be discussed in section 8 of this paper, gives information about the suitable wind turbine need to be installed to maximize the energy output of the wind farm.

The accuracy of quadratic and cubic models reported in the literature varies between 19.11% and 34.46%, respectively [26].

7.2. Root mean square error(RMSE)

RMSE test is a standard metric used to measure the error between estimated and measured values [26]. In this section RMSE is used to measure the error between the energy estimated using quadratic and cubic functions of each wind farms and their measured energy output, using the following expression:

$$RMSE = [\frac{1}{n}\sum_{i=1}^{n}(E_{T_{measured}} - E_{T_{estimated}})^2]^{\frac{1}{2}} \quad (23)$$

Where n is the number of energy data sample used in the study. The index value of the RMSE represents the reliability of the tested model. An index value of '0' or very close to '0' means that the reliability of the tested model is extremely high. The reliability of the tested model is low as long as the index value of RMSE is far from zero.

In order to apply this method, the energy generated by the selected wind farms have been implemented using curve fitting tool of Matlab (2015) to increase the number of samples (n) in Eq. 23. Table 8 shows the RMSE analysis of the quadratic and cubic functions. It is clear that the RMSE of the quadratic models of the selected wind farms are close to zero. Moreover, the cubic models of the selected wind farms show a good value of RMSE, however it is still more reliable to use quadratic models in energy estimation of wind turbines, at least in case of large scale HAWTs.

Table 4. Monthly average wind speed in (m/s) at the hub height for all wind farms.

Location	Year	Hub height(m)	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean
Hofa	2003	45	6.83	8.65	7.88	6.90	6.58	7.71	8.62	7.99	7.76	5.84	5.19	7.13	7.25
Hofa	2003	33.5	6.59	8.34	7.60	6.66	6.35	7.44	8.32	7.71	7.48	5.63	5.00	6.88	7.00
Tafila	2002	45	10.7	9.2	9.69	9.08	7.82	8.16	7.79	7.60	6.28	5.86	8.86	9.38	8.37
Tafila	2002	84	11.5	9.9	10.50	9.75	8.39	8.76	8.36	8.16	6.74	6.29	9.51	10.07	8.98
Fujeij	2011	50	7.08	8.05	6.67	6.78	6.41	7.10	5.88	6.47	5.20	5.09	5.52	6.71	6.41
Fujeij	2011	117	7.78	8.84	7.33	7.45	7.04	7.80	6.46	7.11	5.71	5.59	6.06	7.37	7.04
Al Rajef	2018	50	6.58	6.94	6.44	6.25	6.85	6.74	5.91	6.53	6.20	5.78	6.23	7.07	6.44
Daehan	2018	45	6.21	6.45	6.56	6.39	6.45	6.38	6.21	6.21	6.17	5.93	6.28	6.91	6.23

Table 5. Measured wind energy output in (Mwh) for one year on a monthly basis.

Wind farm	Operator							Measured energy	output in (Mwh)					
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Tafila	JWPC	4150	2300	3300	2600	3300	2900	3800	3700	1700	2200	2200	3500	35650
Hofa	CEGECO	41.8	37.83	49.1	37.13	24.7	55.9	66.6	49.49	33.17	25.6	19.6	32.49	473.41
Al Rajef	GWRE	3150	2480	2950	3530	2540	2970	3050	2220	3350	1970	2580	3570	34360
Daehan	KOSPO	1870	1540	1610	2050	1320	1670	1810	1320	2170	1070	1540	2120	20090

Table 6. Measured vs. estimated wind energy output in (Mwh) using different power curve models.

Wind farm	Turbine model	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Tafila	Measured	4150	2300	3300	2600	3300	2900	3800	3700	1700	2200	2200	3500	35650
	Cubic	4420	2670	3490	2960	3520	3080	4050	3980	1970	2490	2365	3790	38785
	Quadratic	4070	2195	3420	2815	3380	2985	3717	3622	1698	2315	2280	3455	35952
Hofa	Measured	41.8	37.83	49.1	37.13	24.7	55.9	66.6	49.49	33.17	25.6	19.6	32.49	473.41
	Cubic	34.3	31.91	34.4	23.77	18.5	31.9	42.9	27.17	23.77	14.7	10.6	24.93	318.85
	Quadratic	44.1	41.54	45.9	34.74	26.8	52.6	62.8	46.47	32.74	24.3	18.5	34.03	464.52
Al Rajef	Measured	3150	2480	2950	3530	2540	2970	3050	2220	3350	1970	2580	3570	34360
	Cubic	2960	2780	2790	3770	2380	3280	3340	2620	3540	2310	2820	3390	37210
	Quadratic	3070	2670	2880	3480	2470	2890	3120	2370	3390	2080	2420	3410	34250
Daehan	Measured	1870	1540	1610	2050	1320	1670	1810	1320	2170	1070	1540	2120	20090
	Cubic	1920	1410	1890	2390	1680	1480	1570	1610	2490	1350	1650	2570	22010
	Quadratic	1810	1440	1550	2170	1450	1510	1690	1390	2270	1150	1490	2310	20230

Table 7. Percentage error between measured and estimated wind energy output.

Wind farm	Turbine model	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Tafila	Cubic	6.51	16.09	5.76	13.85	6.67	6.21	6.58	7.57	15.88	13.18	7.5	8.29	8.79
	Quadratic	1.93	4.57	3.64	8.27	2.42	2.93	2.18	2.11	0.12	5.23	3.64	1.29	0.85
Hofa	Cubic	17.94	15.65	29.94	35.98	25.1	42.93	35.59	45.1	28.34	42.58	45.92	23.27	32.65
	Quadratic	5.5	9.81	6.52	6.44	8.5	5.9	5.71	6.1	1.3	5.08	5.61	4.74	1.88
Al Rajef	Cubic	6.03	12.1	5.42	6.8	6.3	10.44	9.51	18.02	5.67	79.7	9.3	5.04	8.29
	Quadratic	2.54	7.66	2.37	1.42	2.76	2.69	2.3	6.76	1.19	5.58	6.2	4.48	0.32
Daehan	Cubic	2.67	8.44	17.39	16.59	27.27	11.38	13.26	21.97	14.75	26.17	7.14	21.23	9.56
	Quadratic	3.21	6.49	3.73	5.85	9.8	9.58	6.63	5.3	4.61	7.48	3.25	8.96	0.7

Table 8. Error analysis of quadratic and cubic functions based on RMSE.

Wind farm	RMSE of quadratic model	RMSE of cubic model
Tafila	0.12	0.23
Hofa	0.15	0.28
Al Rajef	0.11	0.25
Daehan	0.13	0.27

8. Capacity factor estimation

The capacity factor, in Eq. 24, reflects how effectively the wind farm could harness the energy available in the wind spectra. [14]:

$$C_F = \frac{E_T}{TP_R}, \tag{24}$$

where C_F is the capacity factor of the wind turbine, and E_T is the energy produced by the wind farm.

In this paper, the capacity factors have been estimated for the three wind farms using the quadratic P-V characteristics only, the most accurate one. Table 9 shows the annual and monthly capacity factors for all wind farms. It was evident that Tafila wind farm has exhibited the highest values of capacity factor compared to other wind farms; since the wind turbines in Tafilah wind farm are effectively utilize the energy available in the wind regime. It is clear that there is a variation in the capacity factor in several months for each wind farm. This variation occurs due to the variation in the interaction between the wind turbines and wind regime for several months.

Table 9. Estimated capacity factors of the wind turbines for the selected wind farms using the quadratic model.

Wind farm	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Mean
Hofa	23.19	36.6	32.25	23.78	21.38	29.84	36.46	31.91	30.15	16.03	11.74	25.48	26.79
Tafila	59.25	52.51	55.42	51.63	42.86	45.47	42.67	41.17	29.94	26.20	50.26	53.35	46.92
Fujeij	42.67	50.04	39.18	40.12	36.66	42.91	31.64	37.34	24.96	23.85	28.07	39.47	37.24
Al Rajef	41.25	45.34	42.38	47.25	33.25	45.54	31.64	35.34	25.56	28.75	29.97	39.52	39.45
Deahan	43.55	49.54	37.98	42.42	38.86	45.51	33.56	33.36	29.11	25.65	27.17	35.27	38.14

9. Conclusion

This paper proposed a power-speed model of the wind turbine by assuming three different functions for the first performance region; cubic, quadratic and uncorrected cubic. The three proposed wind turbine functions were compared with the manufacturer models of five different real wind turbines, which were installed in five different wind farms in Jordan; Tafila, Hofa, Fujeij, Al Rajef, and Deahan. The wind turbine of these wind farms are considered as large scale HAWT. In this study, the quadratic model shows the highest correlation compared with the manufacturer models. The models obtained by cubic and uncorrected cubic functions are less accurate than those obtained by the quadratic models. The energy extracted by the wind farms was estimated using a mathematical model derived in this paper. In order to validate this mathematical model, it was compared with the measured energy output of four wind farms; Tafila, Hofa, Al Rajef, and Deahan. The measured energy output of these wind farms was provided by their operators: JWPC, CEGECO, GWRE, and KOSPO, respectively. Accuracy analysis resulted in an error of less than 10% between the measured and estimated energy for all wind farms. Thus, the validated model can now be utilized routinely for the assessment of wind energy potential of the wind sites. So, a decision can be made whether a wind farm can be built or not in a specific wind site without any need to install anemometers. The capacity factors for the selected wind farms were estimated using the quadratic scenario of the P-V model. The results show that Tafila wind farm has the highest capacity factor which is around 47%.

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