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New method for estimating CF of pitch-regulated wind turbines

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ABSTRACT

This paper presents a new formulation for wind turbine capacity factor (*CF*) estimation using wind speed characteristics at any site and the power performance curve parameters of any pitch-regulated wind turbine. Compared to the existing model, the proposed formulation is simpler and results in more accurate *CF* estimation. The accuracy of the proposed model is verified using measured data from an existing wind farm. Four illustrative case studies and parameter sensitivity analysis are presented to test the effectiveness of the model in turbine-site matching applications.

1. Introduction

Due to wind speed variability, a wind turbine rarely operates at its rated output. Therefore, the Capacity Factor (*CF*) of a turbine is commonly used to estimate its average energy production, which in turn can be used for the economic appraisal of wind power projects at potential sites. Moreover, *CF* models can be used by manufactures and wind power project developers for optimum turbine-site matching, and for the ranking of potential sites [1–4].

The amount of energy produced by a turbine depends on the characteristics of both wind speed at the site under investigation and the turbine's power performance curve. Wind speed at any site is commonly modeled by the Weibull probability density function (pdf), which is characterized by two parameters: the scale factor, c, and the shape factor, k. The turbine's power performance curve can be described by three parameters: the cut-in, nominal, and cut-out speeds. This paper presents a new *CF* model to estimate the *CF* values of modern pitch-regulated wind turbines based on the turbine's power performance curve and the Weibull parameters of wind speed at the site under investigation. The proposed *CF* is generic as it can be used with any order polynomial representation of the ascending segment of the turbine's performance curve. In addition, the paper demonstrates that using the cubic root mean wind speed (*CMWS*) instead of the arithmetic mean wind speed (*MWS*) to determine Weibull pdf wind model parameters changes the actual wind profile; consequently, can result in inaccurate estimation of *CF* values, turbine-site ranking, and design of turbine rated speed.

After this introduction, the paper proceeds with a literature survey devoted to wind power output modeling, which includes wind speed modeling, power curve generic models, and the existing *CF* estimation model. A new generic *CF* model is then proposed in Section 3. Verification of this proposed model's accuracy is presented in Section 4 and its effectiveness is illustrated by four case studies in Section 5. Finally, conclusions are presented.

2. Wind power output modeling

2.1. Wind speed modeling

Wind speed variations are normally described using the Weibull pdf because it gives a good representation of the observed wind speed data [5]. The Weibull pdf is shown in the following formula:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \tag{1}$$

where v is the wind speed in meters per second (m/s); k is a shape factor, and c is a scale factor. The Weibull parameters can be obtained using the mean and the standard deviation of wind speed at the chosen site. The Mean Wind Speed (*MWS*) can be calculated using the following formula.

$$\bar{v} = \int_0^\infty v \cdot f(v) dv \tag{2}$$

The above equation can be written as follows:

$$\bar{v} = c\Gamma\left(1 + \frac{1}{k}\right) \tag{3}$$

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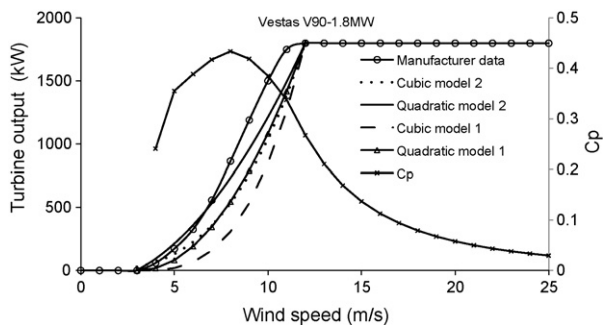

Fig. 1. A graphical comparison of the quadratic and cubic models.

where Γ is the complete Gamma function given by

$$\Gamma(a) = \int_0^{\infty} t^{a-1} e^{-1} dt \tag{4}$$

The standard deviation of wind speed measurements is calculated using the following equation.

$$\sigma = \sqrt{\frac{\sum f(v_i)(v_i - \bar{v})^2}{\sum f(v_i)}} \tag{5}$$

The above formula can be written as follows:

$$\sigma = c\sqrt{\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)} \tag{6}$$

Knowing the mean and standard deviation of wind speed data at the potential site, one can estimate the two parameters of the Weibull function by solving (3) and (6) iteratively.

2.2. Turbine output modeling

The power output P_e of a wind turbine is given as follows [5]:

$$P_e = \frac{1}{2} C_p \rho A_s v^3 \tag{7}$$

where C_p is the turbine coefficient of performance; ρ is the air density in kilograms per cubic meter (kg/m^3), and A_s is the swept rotor area in square meters (m^2). The coefficient value at each wind speed can be found using the following formula:

$$C_p = \frac{P_e}{P_{wind}} \tag{8}$$

The power curve of a pitch-regulated wind turbine is characterized by three speeds: the cut-in, nominal, and cut-out speeds. When the wind speed is below the cut-in speed (V_c), the output power is zero, and the rotor cannot be loaded. At its nominal speed (V_r), the power output is at the rated value (P_{rated}). In response to the power control mechanisms, the power output remains constant as wind speed increases until the cut-out speed (V_f), at which point the turbine will be turned off to prevent mechanical damage. Therefore, P_e can be written as follows:

$$P_e(v) = P_{rated} \times \begin{cases} 0 & v < V_c \text{ or } v > V_f \\ P_{asc} & V_c \le v \le V_r \\ 1 & V_r \le v \le V_f \end{cases} \tag{9}$$

where P_{asc} is the normalized wind turbine output power throughout the ascending segment of the power curve. An example of a turbine output is presented in Fig. 1. For this specific turbine [6], V_c, V_r, and V_f take values of 3, 12, and 25 m/s, respectively. Between V_c and V_r, the turbine output increases as wind speed increases. Manufacturer data show a point of inflection in the ascending segment of the power curve. This point indicates that the turbine efficiency experiences a change at this point. Despite the single point of inflection in the ascending power curve segment, C_p is not constant for most of the speed range. Although, C_p is unique for each turbine and difficult to be generalized, there have been attempts to represent the ascending segment of the power curve by a generic model. By generic, it is meant that a turbine output, as a percentage of rated power, is described using the cut-in and nominal speeds only, without the knowledge of turbine output throughout the ascending segment. Generic models available in open literature include: linear, quadratic, and cubic models [7]. Below is a brief description of each model.

(1) The linear model assumes a linear increase in the turbine output between the cut-in and the nominal speeds. This model, generally, overestimates wind potential. The linear model is given by the following equation:

$$P_{asc}(v) = \frac{v - V_c}{V_r - V_c} \tag{10}$$

(2) Cubic model 1 implicitly assumes a constant overall efficiency of the turbine throughout the ascending segment of the power curve. This model is given by the following formula [7]:

$$P_{asc}(v) = \frac{(v - V_c)^3}{(V_r - V_c)^3} \tag{11}$$

(3) Cubic model 2, considered by the authors in [2,4], is very similar to Cubic model 1. The only difference is the absence of V_c in this model. Cubic model 2 is given by the following equation:

$$P_{asc}(v) = \frac{v^3}{V_r^3} \tag{12}$$

(4) Quadratic model 1 is originally proposed in [8], and coefficients are calculated in [9]. These coefficients are determined based on the assumption that the output of the turbine increases according to the cubic model, Eq. (12), between $(V_c + V_r)/2$ and V_r [8].

$$P_{asc}(v) = a_0 + a_1 v + a_2 v^2 \tag{13}$$

(5) Quadratic model 2, presented in [10], does not have the $(a_1 v)$ term of the previous model.

$$P_{asc}(v) = \frac{v^2 - V_c^2}{V_r^2 - V_c^2} \tag{14}$$

As demonstrated in Fig. 1 and Table 1, the quadratic model presented in [10] gives us the most accurate generic model to represent manufacturer data throughout the ascending segment of the power curve, therefore is used in the derivation of the proposed *CF* model. A better representation of manufacturer data can be achieved by using a higher order polynomial function described by the following equation.

$$P_{asc}(v) = \sum_{i=0}^{n} a_i v^i \tag{15}$$

where n is the order of the polynomial function. However, due to the unique and nonlinear behavior of C_p, coefficients, a_n, are turbine specific and difficult to be generalized. For example, the authors in [11] use a third order polynomial function to represent the turbine output in the ascending power curve segment, and regression is used to find the coefficients (a_n).

2.3. Capacity factor modeling

The average power produced by a wind turbine can be calculated by integrating the power curve multiplied by the Weibull function,

Table 1
Comparison of different power curve models for V90-1.8MW.

Wind speed	pdf[a]	Turbine output (kW)					
		Data [6]	Linear	Cubic 1	Cubic 2	Quadratic 1	Quadratic 2
≤ 3	0.234521	0	0	0	28	0	0
4	0.122592	60	200	2	67	17	93
5	0.126011	173	400	20	130	80	213
6	0.119054	327	600	67	225	188	360
7	0.104705	558	800	158	357	342	533
8	0.086368	865	1000	309	533	541	733
9	0.067145	1190	1200	533	759	786	960
10	0.049363	1500	1400	847	1042	1076	1213
11	0.034399	1750	1600	1264	1386	1411	1493
12–25	0.05584	1800	1800	1800	1800	1800	1800
Annual energy yield (MWh)		4519	5446	2414	3434	3278	4175
Error (MWh)			+927	−2105	−1085	−1241	−344
% Error in *CF*			+20.5%	−46.6%	−24.0%	−27.5%	−7.6

[a] Based on *MWS* = 6 m/s and *k* = 2.

Table 2
Annual wind speed data of Kappadagudda wind power station [4].

Original wind speed data				Reproduced using *CMWS*			
MWS	*SD*	*c*	*k*	*CMWS*	*SD*	*c*	*k*
7.09	3.62	8.0076	2.0765	8.69	3.96	9.8054	2.3503

represented by (1).

$$P_{ave} \int_0^{\infty} P_e(v) f(v) dv \tag{16}$$

The capacity factor is the ratio between the average and the rated power of the turbine. Authors in [2,4] used Cubic model 2, represented by Eq. (12), to derive the existing model for estimating the *CF*.

$$CF = \frac{P_{ave}}{P_{rated}} = \frac{1}{V_r^3} \int_{V_c}^{V_r} v^3 f(v) dv + \int_{V_r}^{V_f} f(v) dv \tag{17}$$

The authors of [4] compared the values of the *CF* obtained from (17) to the measured ones, and found that the model significantly underestimated wind potential at the site under study. To compensate for the mismatch between the modeled and the measured values [4] investigated the effect of using the Root Mean square Wind Speed (*RMWS*) and the Cubic Mean Wind Speed (*CMWS*) to estimate the Weibull function parameters of the wind profile. The authors of [4] found that using the *CMWS* resulted in a better estimation of the *CF*, at the site under study, than using the original (arithmetic) *MWS* and the *RMWS*. The *RMWS* and *CMWS* are defined by the following formulas:

$$RMWS = \sqrt[2]{\frac{\sum f(v_i) v_i^2}{\sum f(v_i)}} \tag{18}$$

$$CMWS = \sqrt[3]{\frac{\sum f(v_i) v_i^3}{\sum f(v_i)}} \tag{19}$$

However, when one compares the original wind profile, obtained using the arithmetic mean wind speed (*MWS*), with that obtained using the *RMWS* or the *CMWS*, a significant difference in the profile is observed. Actually, using the *RMWS* or the *CMWS* shifts the original wind speed data towards higher values, as illustrated in Fig. 2. A comparison between the original wind speed characteristics, for the site under study, and those obtained using the *CMWS* is presented in Table 2 [4].

The authors of [3] solved the integral presented in (17) and devised a *CF* model as a function of the main turbine curve parameters, V_c, V_r, and V_f, and the two parameters of Weibull function, *c* and *k*, that are obtained based on the *CMWS*.

$$CF = \left(\frac{V_c}{V_r}\right)^3 e^{-(V_c/c)^k} - e^{-(V_f/c)^k} + \frac{3\Gamma(3/k)}{k(V_r/c)^3}\left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{3}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{3}{k}\right)\right] \tag{20}$$

where γ is the lower incomplete Gamma function given by

$$\gamma(u, a) = \frac{1}{\Gamma(a)} \int_0^u x^{a-1} e^{-x} dx \tag{21}$$

3. Proposed *CF* model

For an "*n*" order polynomial model for the ascending segment of the power curve of pitch-regulated wind turbines, the new *CF* model is given by the following equation.

$$CF = \frac{P_{ave}}{P_{rated}} = \int_{V_c}^{V_r} \left(\sum_{i=0}^{n} a_i v^i\right) f(v) dv + \int_{V_r}^{V_f} f(v) dv \tag{22}$$

where $f(v)$ is the Weibull pdf, given in (1), and its parameters are based on the *MWS* not the *CMWS*.

Using integration by substitution and by parts [12], the new *CF* model is derived as follows.

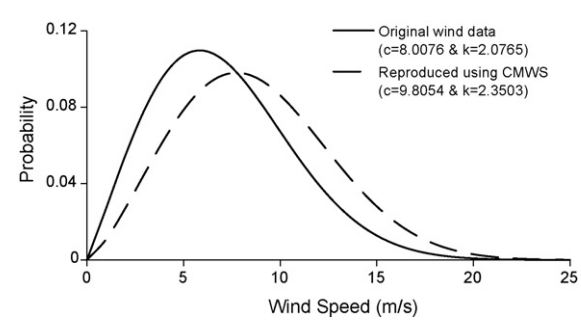

Fig. 2. The effect of using the CMWS to obtain *c* and *k* (data are from [4]).

Assume $x = (v/c)^k$, $dx = k/c(v/c)^{k-1}$, and $cx^{1/k}$, Eq. (22) can be written as a summation of three integrals:

$$CF = I_1 + I_2 + I_3 \tag{23}$$

where $I_1 = a_0 \int_{V_c}^{V_r} e^{-x}dx$, $I_2 = \sum_{i=1}^{n} a_i \int_{V_c}^{V_r} c^i x^{i/k} e^{-x}dx$, and $I_3 = \int_{V_r}^{V_f} e^{-x}dx$ I_1 and I_3 are easily calculated as follows:

$$I_1 = -a_0 e^{-x}|_{x(V_c)}^{x(V_r)} = a_0\left(e^{-(V_c/c)^k} - e^{-(V_r/c)^k}\right) \tag{24}$$

$$I_3 = -e^{-x}|_{x(V_r)}^{x(V_f)} = e^{-(V_r/c)^k} - e^{-(V_f/c)^k} \tag{25}$$

I_2 can be solved using integration by parts [12], where

$$\int_{x_1}^{x_2} udv = uv|_{x_1}^{x_2} - \int_{x_1}^{x_2} vdu \tag{26}$$

where $x_1 = (V_c/c)^k$ and $x_2 = (V_r/c)^k$

Let $u = a_i c^i x^{i/k}$ and $dv = e^{-x}dx$, then, $du = (a_i ic^i/k)x^{(i/k)-1}dx$ and $v = -e^{-x}$, and I_2 can be written as follows:

The second part of (26) can be written as

$$\int_{x_1}^{x_2} \frac{a_i ic^i}{k} x^{(i/k)-1} e^{-x}dx = \int_0^{x_2} \frac{a_i ic^i}{k} x^{(i/k)-1} e^{-x}dx \times \int_0^{x_1} \frac{a_i ic^i}{k} x^{(i/k)-1} e^{-x}dx \tag{27}$$

Eq. (27) can be represented using the complete Gamma function (Γ) and the lower incomplete Gamma function (γ) as follows:

$$\int_0^u x^{a-1}e^{-x}dx = \Gamma(a)\gamma(u, a) \tag{28}$$

Using Eqs. (27) and (28), I_2 can be written so:

$$I_2 = \sum_{i=1}^{n} a_i c^i \left(\left(\frac{V_c}{c}\right)^i e^{(V_c/c)^k} - \left(\frac{V_r}{c}\right)^i e^{(V_r/c)^k} + a_i \frac{ic^i}{k}\Gamma\left(\frac{i}{k}\right) \times \left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{i}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{i}{k}\right)\right]\right) \tag{29}$$

Combining Eqs. (24), (25), and (29), the *CF* model can be written in this way:

$$CF = e^{-(V_r/c)^k} - e^{-(V_f/c)^k} + a_0\left(e^{-(V_c/c)^k} - e^{-(V_r/c)^k}\right) + \sum_{i=1}^{n}\left[a_i c^i\left(\left(\frac{V_c}{c}\right)^i e^{-(V_c/c)^k} - \left(\frac{V_r}{c}\right)^i e^{-(V_r/c)^k}\right) + a_i \frac{ic^i}{k}\Gamma\left(\frac{i}{k}\right) \times \left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{i}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{i}{k}\right)\right]\right] \tag{30}$$

Eq. (30) can be simplified as thus:

$$CF = \sum_{i=0}^{n} a_i V_c^i e^{-k(V_c/c)} + \left(1 - \sum_{i=0}^{n} a_i V_r^i\right) e^{-(V_r/c)^k} - e^{-(V_f/c)^k} + \sum_{i=1}^{n} a_i \frac{ic^i}{k}\Gamma\left(\frac{i}{k}\right)\left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{i}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{i}{k}\right)\right] \tag{31}$$

Table 3
A comparison between measured and calculated annual *CF*.

	CF value	Error
Measured CF [4]	0.290	–
Calculated using the existing model [3]	0.388	33.80%
Calculated using the proposed model	0.307	5.86%

Table 4
Turbine-site selection for Kappadagudda.

Turbine parameters				*CF*	
Sl. no.	V_c	V_r	V_f	Existing model	Proposed model
12	4.3	7.7	17.9	0.7104	0.5557
9	3	10	25	0.5787	0.4667
10	4	10	25	0.5763	0.4362
7	3	13	25	0.3882	0.318
6	3.5	13	20	0.3831	0.3056
8	4	13	25	0.3871	0.2945
5	5.5	12	24	0.4386	0.2896
1	3.5	13.5	25	0.3604	0.2875
2	3.5	13.8	25	0.3446	0.2765
4	5	12.9	24	0.3895	0.2705
3	5	13	25	0.3841	0.2668
11	4	14	28	0.3339	0.2581

Because $P_e(V_c) = 0$ and $P_e(V_r) = 1$, the above equation could be further simplified as follows:

$$CF = -e^{-(V_f/c)^k} + \sum_{i=1}^{n} a_i \frac{ic^i}{k}\Gamma\left(\frac{i}{k}\right) \times \left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{i}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{i}{k}\right)\right] \tag{32}$$

The above equation is independent of a_0 and can be used for any "n" order polynomial representation of the power curve. The *CF* model based on Quadratic model 2 can be calculated by substituting $a_1 = a_3 = a_4 = 0$ and $a_2 = 1/(V_r^2 - V_c^2)$ in Eq. (32).

$$CF = -e^{-(V_f/c)^k} + \frac{1}{V_r^2 - V_c^2}\frac{2c^2}{k}\Gamma\left(\frac{2}{k}\right) \times \left[\gamma\left(\left(\frac{V_r}{c}\right)^k, \frac{2}{k}\right) - \gamma\left(\left(\frac{V_c}{c}\right)^k, \frac{2}{k}\right)\right] \tag{33}$$

For sites at which wind distribution can be represented by the Rayleigh distribution ($k = 2$ and $c = 1.128\bar{v}$), the above formula can be further simplified to the following equation:

$$CF = -e^{-(V_f/c)^k} + \frac{1.273\bar{v}^2}{V_r^2 - V_c^2}\left[\gamma\left(\frac{V_r^2}{1.273\bar{v}^2}, 1\right) - \gamma\left(\frac{V_c^2}{1.273\bar{v}^2}, 1\right)\right] \tag{34}$$

4. Model verification

To verify the accuracy of the proposed model, which is represented by Eq. (33), wind speed data and the measured *CF* at Kappadagudda wind power station [4] are used. Wind speed data at the site are presented in Table 2. A comparison of the calculated *CF*, including the existing model and the proposed one, and the measured values are presented in Table 3. The power performance curve parameters of Turbine 1, presented in Table 4, are used in the *CF* calculation as in [4].

The results show that the proposed model gives more accurate *CF* estimations. The mismatch between the annual *CF* calculated using the proposed model and the measured value is less than 6%.

Table 5
Wind speed characteristics.

Original data			Using *CMWS*		
MWS	*c*	*k*	*CMWS*	*c*	*k*
6	6.770	2	7.444	8.403	2.307
7	7.899	2	8.682	9.800	2.301
8	9.027	2	9.903	11.178	2.297
9	10.155	2	11.064	12.490	2.292
10	11.284	2	12.114	13.675	2.284
11	12.412	2	13.012	14.690	2.267
12	13.541	2	13.742	15.516	2.237

Although the existing model is based on a model of the turbine performance curve that underestimates wind production during the ascending segment of the power curve, it overestimates the annual *CF* by 34% at this specific site. This phenomenon can be attributed to the use of the *CMWS* instead of the *MWS* in estimating the Weibull parameter; therefore, the original wind profile is shifted towards higher speeds.

It is worth mentioning that with an accurate turbine power curve model, and an accurate probability distribution model of wind speed data at a given site, calculated *CF* values are expected to be higher than measured. This phenomenon is attributable to energy losses that occur due to many reasons such as wake effect, reduced blade efficiency due to soiling, electrical losses between the turbine and the grid, and availability of both the turbines and the grid. In addition, turbine power curves are obtained at certain conditions, such as air density, which might differ from that at sites at which turbines are installed.

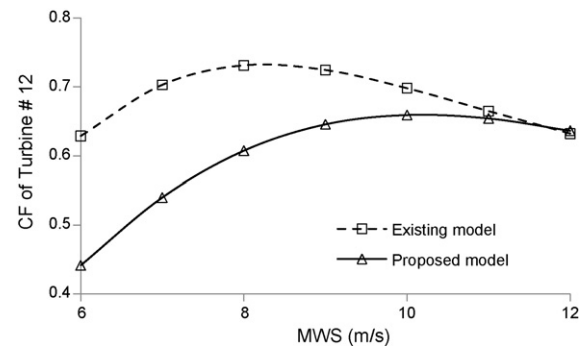

Fig. 3. *CF* of Turbine 12 as a function of the site's *MWS*.

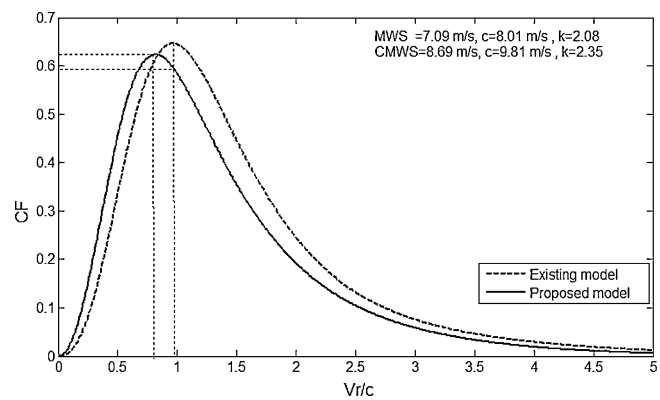

Fig. 4. *CF* as a function of the normalized nominal speed (V_r/c).

5. Illustrative case studies

5.1. Turbine-site selection

In a turbine-site selection problem, the turbine that yields the highest *CF* at a specific site is the best match for that site. The power curve parameters, V_c, V_r, and V_f, of 12 turbines are presented in Table 4 [4]. The annual wind speed data at Kappadagudda wind power station [4], presented in Table 2, is used to calculate the *CF* for each turbine, using both the existing and the proposed models. In Table 4, the turbines are ranked according to the highest annual *CF* calculated using the proposed model. The results reveal that the existing model overestimates the captured wind energy for all turbines.

From a wind energy capture perspective, for either model, Turbine 12 is by far the best match for this site, because this turbine has the lowest nominal speed, V_r. Both models yield similar results for the 2nd and the 3rd best match due to the relatively low V_r of Turbines 9 and 10. However, for the 4th best match and beyond, there is a significant difference in turbine ranking. For example, while Turbine 7 is the 4th best match according to the proposed model, it is the 6th best option when using the existing model.

5.2. Effect of MWS on turbine-site selection

The previous subsection investigated the turbine-site selection for a given site with specific wind parameters. In this subsection, the effect of the *MWS*, which determines the Weibull function scale factor, *c*, is studied. Seven *MWS* scenarios are considered: 6–12 m/s. For the sake of comparison, the shape factor, *k*, of 2 is assumed. The existing *CF* model uses the Weibull parameters, *c* and *k*, based on the *CMWS* calculated by Eq. (19). To calculate these parameters from the original data, Eq. (5) is used to obtain σ_{CMWS}. Then, Eq. (35) is iteratively solved for *k*. Finally, Eq. (3) is used to find *c*. A summary

Table 6
Turbine-site ranking for different *MWS* scenarios.

Rank	6 m/s		7 m/s		8 m/s		9 m/s		10 m/s		11 m/s		12 m/s	
	CF1	*CF2*	*CF1*	*CF2*	*CF1*	*CF2*	*CF1*	*CF2*	*CF1*	*CF2*	*CF1*	*CF2*	*CF1*	*CF2*
1st	12	12	12	12	12	12	12	12	12	9	9	9	9	9
2nd	9	9	9	9	9	9	9	9	9	10	10	10	10	10
3rd	10	10	10	10	10	10	10	10	10	12	12	12	12	5
4th	7	5	7	5	7	5	7	5	7	5	7	5	7	7
5th	6	7	6	4	6	4	5	7	5	7	5	7	5	8
6th	8	4	8	7	5	7	8	8	8	8	8	8	8	3
7th	1	6	5	8	8	8	6	4	1	3	1	3	1	12
8th	2	8	1	3	1	3	1	3	4	4	3	4	3	11
9th	5	3	2	6	2	6	4	1	3	1	4	1	11	4
10th	4	1	4	1	4	1	3	2	2	11	2	11	2	1
11th	3	2	3	2	3	2	2	6	6	2	11	2	4	2
12th	11	11	11	11	11	11	11	11	11	6	6	6	6	6

of wind speed data is presented in Table 5.

$$\left(\frac{\bar{v}_{CMWS}}{\sigma_{CMWS}}\right)^2 = \frac{\Gamma^2(1+(1/k))}{\Gamma(1+(2/k)) - \Gamma^2(1+(1/k))} \tag{35}$$

The ranking of the turbines for all wind speed scenarios, based on the *CF* estimated using the proposed (*CF1*) and existing models (*CF2*), is presented in Table 6. For 6, 7, 8, and 9 m/s *MWS* scenarios, Turbine 12 yields the highest *CF* when using either model. This result is attributed to the fact that this turbine has the lowest V_c. However, for the higher *MWS* scenarios, 10, 11, and 12 m/s, using the existing model results in a lower ranking of this turbine compared to that obtained using the proposed model. For the 12 m/s *MWS* scenario, Turbine 12 is ranked the 3rd best option using the proposed model compared to being the 7th best option using the existing model. This phenomenon is attributable to the fact that using the *CMWS* to estimate the Weibull function parameters shifts the original wind speed data towards higher values, as illustrated in Fig. 2. Consequently, due to its low V_r, the existing model results in estimating more non-captured wind energy, due to too high wind speeds, than actually happens. This phenomenon causes the value of the *CF* estimated using the existing model to peak at 8 m/s compared to 10 m/s with the proposed model (see Fig. 3). Interestingly, at an *MWS* scenario of 12 m/s, using the proposed model yields a higher *CF* compared to that obtained using the existing model for reasons described above and illustrated in Fig. 2.

5.3. Turbine nominal speed design

The proposed model can be used to design the optimum turbine nominal speed, V_r for a specific site [3]. In Fig. 4, the values of the *CF* calculated using both models are plotted against the normalized nominal turbine speed (V_r/c), where c is based on the *MWS* for Kappadagudda wind power station. The turbine power curve parameters are as in [3]. As demonstrated by the figure, there exists an optimum value for the normalized nominal speed at which the maximum wind energy capture occurs. The results demonstrate that if the existing model is used, the optimum design value is shifted to the right. This phenomenon is attributed to the use *CMWS* in obtaining the Weibull parameters. The results show that the proposed model yields a lower optimum (V_r/c) design ratio compared to that obtained using the existing model. Consequently, the optimum ratio obtained from the proposed model will yield about 5% more energy from the same turbine.

5.4. Sensitivity analysis

In this subsection, *CF* sensitivity analysis is presented to demonstrate the effectiveness of the proposed model. Fig. 5 illustrates the effect of the Weibull pdf shape factor, k, on the optimum design of the normalized nominal speed for a typical turbine with ($V_c/V_r = 0.275$) and ($V_f/V_r = 1.85$) [3]. The (V_r/c) design ratio decreases slightly from 0.71 to 0.84 as k increases from 1.5 to 3.

Fig. 6 illustrates the effect of the shape factor, k, on the *CF* calculated for different *MWS* scenarios. It is worth mentioning that for each *MWS* scenario, there exists a value for k, at which point the *CF* is at its maximum value. Additionally, the calculated *CF* drops dramatically for k values less than 1. This phenomenon does not happen in practice for most potential wind project sites, as the shape factor of the annual wind speed pdf takes values between 1.5 and 3.5.

In Fig. 7, the *CF*, as a function of the *MWS*, is plotted for different values of k. There exists an approximately linear relationship between the calculated *CF* and the *MWS*. The results illustrate that for *MWS* less than 7 m/s, lower values for k result in better wind energy capture. On the other hand, for *MWS* higher than 7.5 m/s, better *CF* values are achieved for sites at higher k values than those obtained from sites at which wind speed is characterized by lower k values.

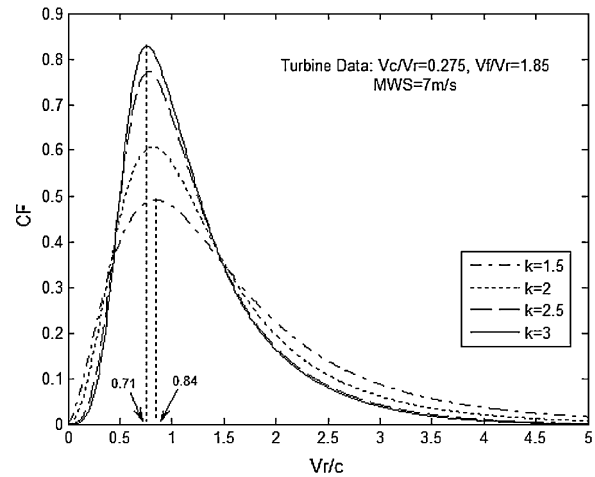

Fig. 5. Effect of the shape factor, k, on V_r/c design.

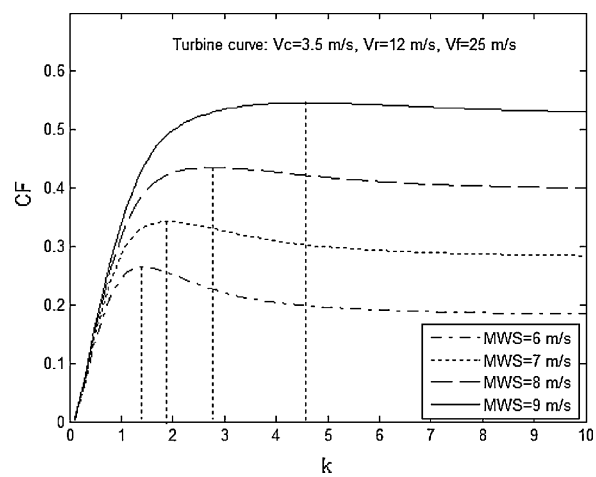

Fig. 6. *CF* as a function of the shape factor for different *MWS*.

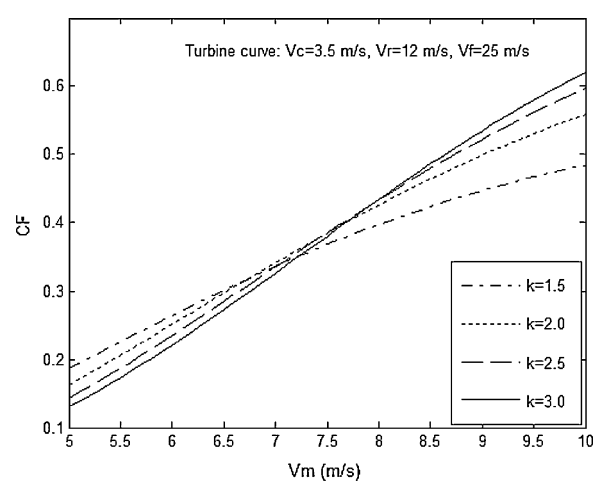

Fig. 7. Effect of *MWS* on *CF* for different k factor scenarios.

6. Conclusions

This paper presents a new, simpler formulation for a pitch-regulated wind turbine capacity factor model, based on the Weibull pdf parameters of the wind speed at any site and the turbine power

performance curve. The accuracy of the proposed model over that of the existing one is verified using measured data. While the existing model overestimates the annual wind potential at the site under study by 34%, the mismatch between the measured and estimated *CF* using the proposed model is less than 6%. Four illustrative case studies and parameter sensitivity analysis are presented to highlight the effectiveness of the new model in turbine-site matching applications. Due to its accuracy, using the proposed model leads to more accurate ranking of wind turbine candidates for installation at certain potential sites. Moreover, when used to design the optimum normalized nominal speed of a turbine for a specific location, the proposed model can lead to about 5% more wind energy capture than that with the existing model. Finally, sensitivity analysis is presented to illustrate the effect of model parameter change on the estimated *CF* values.

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