Wind turbine selection and wind farm design in Tindouf

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Abstract

The aim of this paper is to evaluate the wind resource on the site of Tindouf, in South Algeria. The data used in this study span a period five years from 2009 to 2014. The average power density, energy produced and cost of kWh was evaluated based on the frequency of the speed and the temperature collected, while the wind direction frequencies are used to plotting the wind rose, in order to choose the appropriate site for the future wind turbine. The best planning for an 18 MW wind farm is in two rows, where the distance between these two rows equal to 520m, the first row consists of 12 wind turbines Wgt800kW and the second range consists of 11 wind turbines of the same type, the distant between wind turbines is 208 m along the North (N) to South (S).

Keywords: *Wind power, wind farm, wind rose, Algeria*

1. Introduction

The last century is a century of exhaustion of fossil energy that affects the environment, and so at the beginning of this century it seems that renewable energy is competitive, especially wind energy, where the total wind generation capacity installed in the world range from 7.48 GW in 1997 to 439.19 GW in 2015, a rise of more than 58 times in 18 years and an increase of 17% over the last year (from 2014 to 2015) [1]. As for the Maghreb countries, they have begun to exploit wind power and the total installed in the three countries Morocco, Tunisia and Algeria respectively have 787MW, 245MW and 10MW[1].

The region of Tindouf has a desert aspect, it is essentially formed by the Hamada, The northern part is occupied by some rocky mountains (Djebel Ouarkziz), to the south is the massif (Eglab), this one is separated from the zone of Hamada by the (Erg Egguid) [2].This region is recognized by the desert climate, characterized by low rainfall, high temperatures for a longer period and low humidity[3]. This explains the low proportion of the population in this region, where the population equal to 49149 inhabitants [4].

The Algerian State has sought to develop renewable energies for the first two purposes: to conserve fossil energy and diversify energy sources. The second objective is to achieve sustainable development, especially in the desert areas, in order to stabilize the local population and encourage the inhabitants of the North to live in these areas.

Much Atlas wind of Algeria shows that Tindouf is one of many sites with very good wind potential, Suitable for setting up wind farms. In particular, we can cite the work of F.Chellali et al. (2011)[5] contributed to the updating of the Algerian wind map as well as the study of Hassi R'Mel and also the improvement of The Atlas wind by S. M Boudia (2013) [6].

Benmejahed et al. (2016) [7], stressed that Tindouf is considered a favourable zone for the development of wind energy because it belongs to class (03) of the PNL (Pacific Northwest Laboratory) classification.

The present study attempts to determine the stage to be followed for the choice of wind turbines and the design of the wind farm, to start processing and simulation of the collected data (wind and temperature) every 3hour over five years, after the estimation of wind energy and the economic evaluation was carried out for the wind farm (18 MW). We select the appropriate wind turbine of 8 types of the wind turbines, according to the lowest cost possible for the unit of energy possible.

2. Power & Energy

2.1. Wind power

The power of the wind which runs at a speed v by a section S with a density of air ρ, we can be expressed by the following equations [7–13]:

$$P = \frac{1}{2}\rho S v^3 \tag{1}$$

The reference air density (1.225kg/m³) is employed in the curves of power for the manufacturers of the wind turbine is obtained under standard conditions (T = 15 C and P = 1013.3 mbar).But the air density is a local parameter where it depends on the atmospheric pressure and the temperature of the site; by supposing that the air is a perfect gas we can conclude the following report [14]:

$$\rho = \frac{335.49}{T}\exp\left(-0.034\frac{Z}{T}\right) \tag{2}$$

The logarithmic law is selected to extrapolate the measured wind speed v_1 at the reference height h_1 to estimated wind speed v_2 at the hub wind turbine height h_2, we can be expressed by the following equation [15]:

$$v_2 = v_1 \frac{\log\left(\dfrac{h_2}{z_0}\right)}{\log\left(\dfrac{h_1}{z_0}\right)} \tag{3}$$

The wind turbine can converted the aerodynamic power into the electric power, where the electric power can be written as follows [8] :

$$P_e = C_e P \tag{4}$$

The efficiency wind turbine (C_e) can be written as follows [10]:

$$c_e = c_p \eta_m \eta_g \tag{5}$$

The wind turbines parameters for standard models are presented in Table1 and the powers curves of the selected wind turbines are illustrated in fig.1.

The superposition of the power curve (kW) and the frequency histogram give the annual average wind power [7]:

$$\overline{P} = \sum_{v_i=v_d}^{v_a} P_e(v_i)H(v_i) \tag{6}$$

We calculated the annual average of the power density for stated site for 8 wind turbine (rated power varies from 500kW to 3600kW).The results obtained are illustrated in [16].

The power density range from 71.73 W/m² (Wgt500kW) to 89.64 W/m² (Wgt 1.8MW).On notes that the density of power depends on the climatic conduits on the site (speed and temperature of the wind) as well as the efficiency wind turbine.

2.2. *Wind energy*

When several wind turbines are installed in block, turbulence due to the rotation of the blades of a turbine can affect the turbines in the vicinity. In order to minimize the effect of this turbulence induced by the rotor, a spacing of order 3 to 4 D (D is the diameter of the rotor) is provided inside the lines (In general, the loss of energy because of the effect of park is approximately 5%).The Total annual energy produces by a wind farm can be calculated by the following equation [7]:

$$E_T = (1 - 0.05)NE_w \qquad (7)$$

Where N is the number of wind turbines in the wind farm and Ew is recoverable energy over one year for a wind turbine [7]:

$$E_w = \overline{P} \times 8760 \qquad (8)$$

We chose to install a wind farm (18MW).we estimated the energy produced by the various types of wind turbine (see table 2):

From table 2, we noted that the maximal energy, it produced by the wind farm composed of 23 wind turbine (Wgt 800kW) equal to 42.88 GW, while the energy produced by other wind farm range from 23.11GW produced by the wind farm composed of 36 wind turbine (Wgt 500kW) to 42.85 produced by the wind farm composed of 8 wind turbine (Wgt 2.6MW).The energy produced depends on the diameter of the wind turbine, therefore swept surface increases with increase in the diameter of the wind turbine.

3. Energy Cost

3.1. *Initial cost*

The initial cost is equal to the sum of the components costs. The total cost is given by [7, 8, 17–19]:

$$IC = C_{wt} + C_{st} + C_{en} + C_{ci} + C_{tr} + C_{el} + C_{misc} \qquad (9)$$

The wind turbine cost can be given as follows [17, 20]:

$$C_{wt} = C_{spe} P_R \qquad (10)$$

Where Pr is the rated power and C_{spe} is the specific cost of the wind turbine. It is given in table 3.

Form table 4, it can be observed that the average initial cost for wind farm composed of 23 wind turbine (Wgt800kW) and the wind farm composed of 8 wind turbine (Wgt2.3 MW) equal to 29.90 million $, while it is cheaper for others wind farms, where it represents 29.25 million $.

3.2. *Present value of cost*

The estimate of the Present value of cost and the maintenance cost for the wind farms, on the site considered was carried out according to following assumptions [17]:
- The lifetime of the Wgt (n) was assumed to be 20 years;
- The discount rate (r) was taken as 8%;
- The escalation ratio of operation and maintenance (e_m) was assumed to 6%;
- The operation and maintenance cost for the first year (C_{om}) was considered to be 25%;
- It is assumed that the Wgt produces equal amount of energy output in each year during its useful lifetime.

The Present value of cost is defined by[18]:

$$PVC = CRF \times IC + C_{om(p)} \tag{11}$$

$C_{om\ (p)}$ represents the cost of maintenance during the lifespan of the system ($). It can be calculated as follows [17, 20]:

$$C_{om(p)} = \frac{C_{oma}}{1-e_m}\left[1-\left(\frac{1+e_m}{1+r}\right)^n\right] \tag{12}$$

CRF is the actualisation factor, defined by [20]:

$$CRF = \frac{r}{1-(1+r)^{-n}} \tag{13}$$

Form fig.3, it can be observed that the average present values of cost equal to 5.53 million $ and the average maintenance cost equal to 2.48 million $ for the wind farm composed of 23 wind turbine (Wgt800kW) and the wind farm composed of 8 wind turbines (Wgt2.3 MW), while the average present values of cost and the average maintenance cost for the other wind farm are 5.41 million $ and 2.43 million $ respectively.

3.3. Electricity Cost

The cost of produced kWh is the ratio of present value of costs PVC of project on produced electricity E_T [20]:

$$UCE = \frac{PVC}{E_T} \tag{14}$$

Form table 5, it can be observed that the low cost of kWh equal to 0.1290 $/kWh produced by the wind farm composed of 23 wind turbine (Wgt800kW), while cost of kWh for the other wind farm range from 0.1435 produced by the wind farm composed of 18 wind turbine (Wgt1MW) to 0.2341 produced by the wind farm composed of 36 wind turbine (Wgt500kW).

4. Wind Farm design

4.1. Wind rose

The statistical analyse of the wind direction data used to determine the wind rose, which represents the wind frequency according to the direction in a polar reference [8].
Form fig.4, it can be observed that the western sector is dominant direction, which the frequency represents 20%, while the frequency of the predominant direction (SWS) equal to10%.

4.2. Wind turbine selection

Tindouf is characterized by favourable surfaces for wind turbine development areas, we chose a powerful wind turbine, which the cost of the kWh produced is the cheapest. The best planning for an 18 MW wind farm is in two rows, where the distance between these two rows equal to 520m, the first row consists of 12 wind turbines Wgt800kW and the second range consists of 11 wind turbines of the same type, the distant between wind turbines is 208 m along the north (N) to South (S).The geographical planning of wind farm is illustrated in fig. 5 and virtual wind farm is illustrated in fig.6.

The Wind turbines are large structures installed in open areas, which make them visually important in the landscape. It can disturbed by predominate our gaze up to 2 km or more. They are often perceived as an important element in the landscape at a distance of 5 km, but the wind farms constructed astutely can be a positive addition to landscapes and with presentations naturally blended with landscapes and turbines designed with an aesthetic sense, can add to the scenic beauty of the landscape.

5. Conclusion and implications

This study focused on the evaluation of the wind potential and the cost per kW of energy produced for Tindouf in the Algerian Sahara, to a five-year (from 2009 to 2014) .The power density range from 71.73 W/m² (Wgt500kW) to 89.64 W/m² (Wgt 1.8MW); the density of power depends on the climatic conduits on the site (speed and temperature of the wind) as well as the efficiency wind turbine. However the maximal energy, it produced by the wind farm composed of 23 wind turbine (Wgt 800kW) equal to 42.88 GW, while the energy produced by other wind farm range from 23.11GW produced by the wind farm composed of 36 wind turbine (Wgt 500kW) to 42.85 produced by the wind farm composed of 8 wind turbine (Wgt 2.6MW); the energy produced depends on the diameter of the wind turbine, therefore swept surface increases with increase in the diameter of the wind turbine.

The average initial cost for wind farm composed of 23 wind turbine (Wgt800kW) and the wind farm composed of 10 wind turbine (Wgt1.8 MW) equal to 29.90 million $, while it is cheaper for others wind farms, where it represents 29.25 million $, this means that the present values of cost equal to 5.53 million $ and the maintenance cost equal to 2.48 million $ for the wind farm composed of 23 wind turbine (Wgt800kW) and the wind farm composed of 8 wind turbines (Wgt1.8 MW), while the Present values of cost and the maintenance cost for the other wind farm are 5.41 million $ and 2.43 million $ respectively, we can conclude that the low cost of kWh equal to 0.1290 $/kWh produced by the wind farm composed of 23 wind turbine (Wgt800kW), while cost of kWh for the other wind farm range from 0.1435 produced by the wind farm composed of 18 wind turbine (Wgt1MW) to 0.2341 produced by the wind farm composed of 36 wind turbine (Wgt500kW),but the unite cost energy by produced fossil energy in Algeria equal to 0.054 $/ kWh[17] .

We used the wind direction frequencies to plot the wind rose and the results showed that the western sector is the dominant direction, which the frequency represents 20%, while the frequency of the predominant direction (SWS) equal to10%. Therefore the best planning for an 18 MW wind farm is in two rows, where the distance between these two rows equal to 520m, the first row consists of 12 wind turbines Wgt800kW and the second range consists of 11 wind turbines of the same type, the distant between wind turbines is 208 m along the north (N) to South (S); In this case the Wind turbines are large structures installed in open areas, which make them visually important in the landscape. It can disturbed by predominate our gaze up to 2 km or more. They are often perceived as an important element in the landscape at a distance of 5 km, but the wind farms constructed astutely can be a positive addition to landscapes and with presentations naturally blended with landscapes and turbines designed with an aesthetic sense, can add to the scenic beauty of the landscape.

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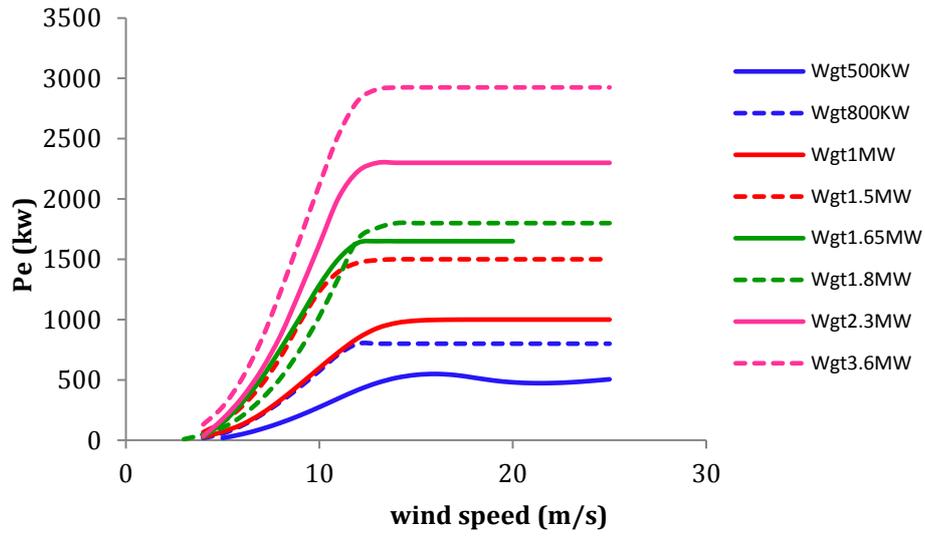
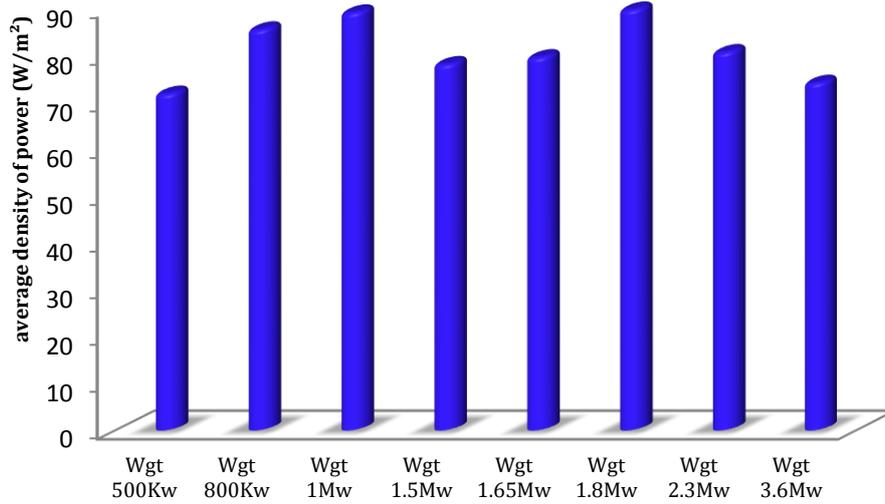Figure 1 Powers curves of the selected wind turbines [16].

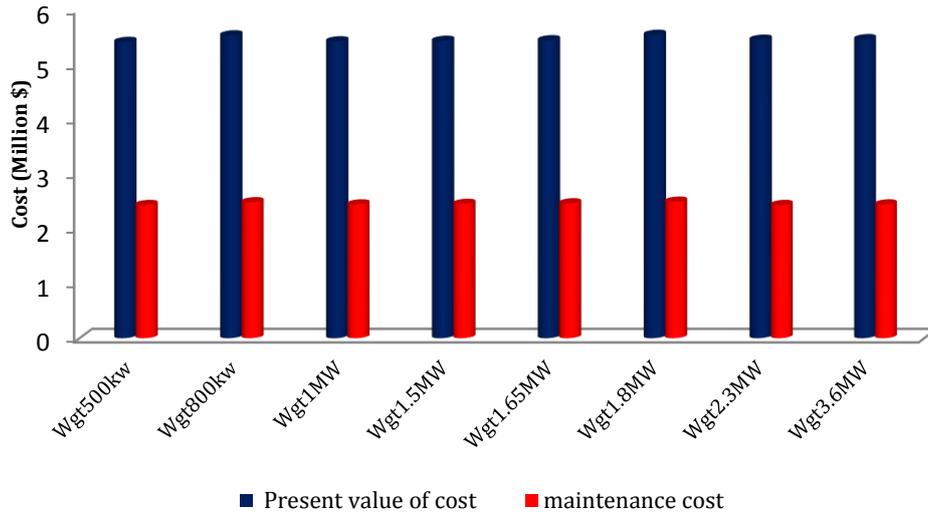Figure 2 Annual average of power density in Tindouf.

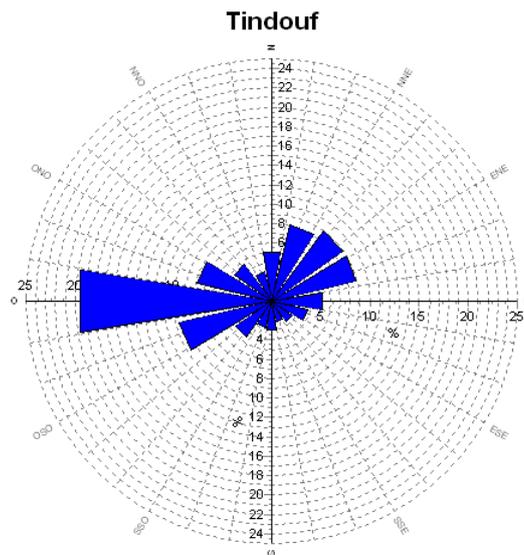Figure 3 The Present value of cost and the maintenance cost for wind farm (18MW)
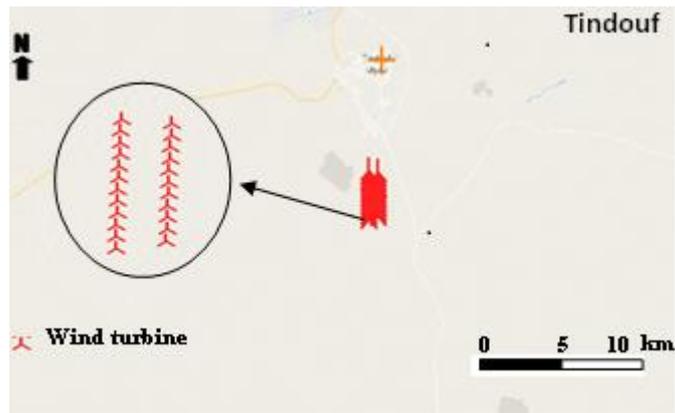

Figure 4 Annual wind rose.

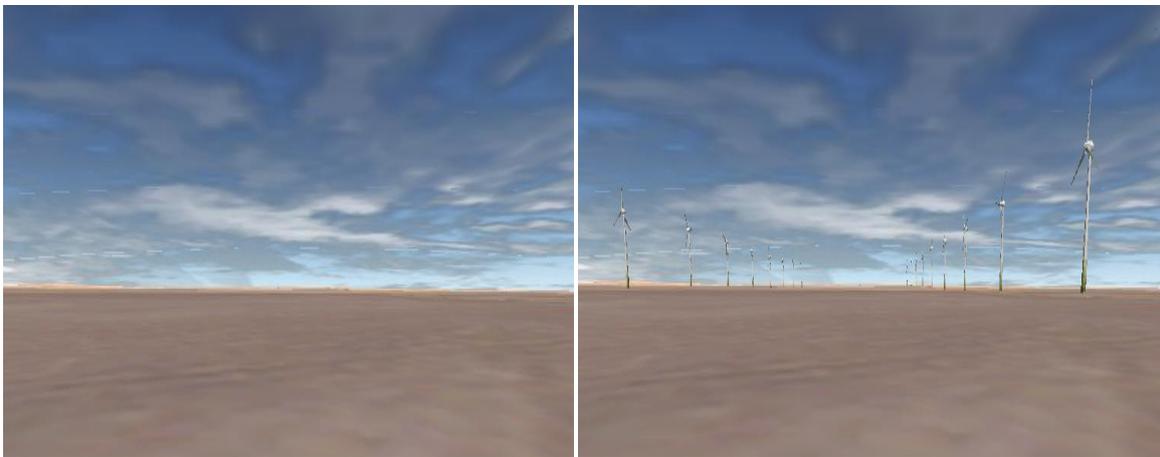Figure 5 Planning for wind farm (18 MW) in Tindouf

Figure 6 Simulation of the visual impact of wind turbines on the landscape in Tindouf.

Table 1 Standard wind turbine parameters [16]

Wind turbine	Name	Pr (kW)	D(m)	h_2 (m)	V_d(m/s)	V_a(m/s)
Wgt 500kw	NORDTANK 500kW	500	37	42.3	5	25
Wgt 800kw	MADE A-52	800	52	50	4	25
Wgt 1Mw	BONUS 1MW	1000	54.2	60	4	25
Wgt 1.5 Mw	GAMESA G80	1500	80	78	4	25
Wgt1.65Mw	VESTAS NM82	1650	82	78	4	20
Wgt 1.8 Mw	ENERCON E-66	1800	70	98	3	25
Wgt 2.3 Mw	NORDEX N90	2300	90	80	5	25
Wgt 3.6 Mw	SIEMMENS SWT-3,6	3600	107	90	5	25

Table 2 Wind energy produced by the wind farm (18MW)

Wind turbine	N	E_W	E_T
Wgt500kW	36	0.68	23.11
Wgt800kW	23	3.76	42.88
Wgt1MW	18	4.96	37.70
Wgt1.5 MW	12	1.45	31.72
Wgt1.67 MW	11	0.22	24.94
Wgt1.8 MW	10	7.06	33.54
Wgt2.3 MW	8	4.10	42.85
Wgt3.6 MW	5	2.50	23.72

Table 3 Specific cost of wind turbine [18]

Wind turbine size (kW)	Specific cost (USD/kW)
10–20	2200–2900
20–200	1500–2300
200>	1000–1600

Table 4 Initial cost for wind farm (18MW).

		C_{wt}	C_{st}	C_{en}	C_{ci}	C_{tr}	C_{el}	C_{misc}	IC
	Cost (%)	75	2	5	8	2	7	1	100
Cost (Million $)	Wgt500kW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25
	Wgt800kW	23.92	0.48	1.20	1.91	0.48	1.67	0.24	29.90
	Wgt1MW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25
	Wgt1.5 MW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25
	Wgt1.65 MW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25
	Wgt1.8 MW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25
	Wgt2.3 MW	23.92	0.48	1.20	1.91	0.48	1.67	0.24	29.90
	Wgt3.6 MW	23.40	0.47	1.17	1.87	0.47	1.64	0.23	29.25

Table5Costs of kWh produced by a wind farm 18 MW.

Wind turbine	UCE (kWh)
Wgt500kW	0.2341
Wgt800kW	0.1290
Wgt1MW	0.1435
Wgt1.5 MW	0.1706
Wgt1.65 MW	0.2185
Wgt1.8 MW	0.1613
Wgt2.3 MW	0.1291
Wgt3.6 MW	0.2281

Nomenclature

C_{ci}	civil work and installation cost ($)
C_e	efficiency wind turbine
C_{el}	cost of electrical connection ($)
C_{en}	engineering cost ($)
C_{misc}	miscellaneous cost ($)
C_{om}	maintenance cost for the first year ($)
$C_{om}(p)$	cost of maintenance during the lifespan ($)
C_p	Coefficient of power
CRF	actualisation factor
C_{spe}	specific cost ($/kW)
C_{st}	Study cost ($)
C_{tr}	cost of transport ($)
C_{wt}	cost of the wind turbine ($)
D	wind turbine diameter (m)
E_W	energy generated by wind turbine (kWh)
e_m	escalation ratio of operation and maintenance (%)
E_T	energy generated by wind farm (kWh)
H(v)	frequency histogram
h_1	reference height (m)
h_2	wind turbine hub height
IC	initial cost ($)
N	number wind turbine
n	wind turbine lifetime (years)
P	aerodynamic wind power (kW)
Pe	electrical wind power (kW)
Pr	rated power (Kw)
$\overline{P}$	average wind power (kw)
PVC	present value of cost ($)
r	discount rate (%)
S	area swept by the wind turbine (m²)

T	temperature (°k)
v	wind speed(m /s)
v_1	measured wind speed (m/s)
v_2	estimated wind speed
v_a	Cut-out wind speed (m/s).
v_d	Cut-in wind speed (m/s)
z	altitude (m)
z_0	roughness height (m)
ρ	air density (kg/m^3)
η_g	generator output
η_m	multiplier output