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Assessment of the Resources of Wind Energy in Various Regions of Algeria

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ABSTRACT

Details on the wind potential during a period of about thirteen years in Algeria is given in the present work. The inspection is performed for sixteen regions covering almost all the territory of the country. The density of the mean wind power is determined for the different regions. The maps of annual and seasonal wind energy resources are also established. The characteristics of the wind velocity, as well as the potential of wind power, are determined by the Weibull distribution. From the given results, the highest values of annual mean wind speed and the annual mean wind power density are found in Adrar (P_{10} = 283.12 W/m^2 and P_{50} = 646.91 W/m^2), while the lowest values are observed in Skikda (P_{10} = 40.61 W/m^2 and P_{50} = 115.51 W/m^2, respectively).

1. INTRODUCTION

The quantity of available energy for the reserves of fossil fuel changes seasonally and daily. However, and for the wind, the determination of its resources remains really difficult, since its power is affected by topography, contrary to the solar energy. In addition, the characteristics and distribution of the wind-engines have a significant impact on the wind conversion in the same region. In the literature, some scientific studies assessed the Algerian potential of wind. The design of systems and techniques to covert the wind energy in this country was also discussed by some authors. Amon other works, Himri et al. [1, 2] presented details on the wind power in the south of Algeria. Maouedj et al. [3-5] interested in various regions of Algeria. Aksas et al. [6] analyzed wind energy at Batena (Algeria) during the period of 1999-2008. Benmedjahed et al. [7-11] reviewed the potential of wind energy in some regions of Algeria. Only few studies [12-15] participated in the map actualization of this country by adding other sites and other parameters in the assessment of wind resources. Other experimental on the wind energy in different regions of Algeria may be found in Refs. [16-22].

The objective of this survey is to explore the resources of the Algerian wind by using the meteorological data, the temperature and direction of the wind. An effort was made to evaluate the energy potential of various regions and to conduct a classification of these regions.

2. REGIONS UNDER STUDY

Sixteen regions were considered in this study. Their geographical positions are given in Figure 1 and Table 1. Data for the explored regions were given from the Algerian Meteorological National Office [12, 23].

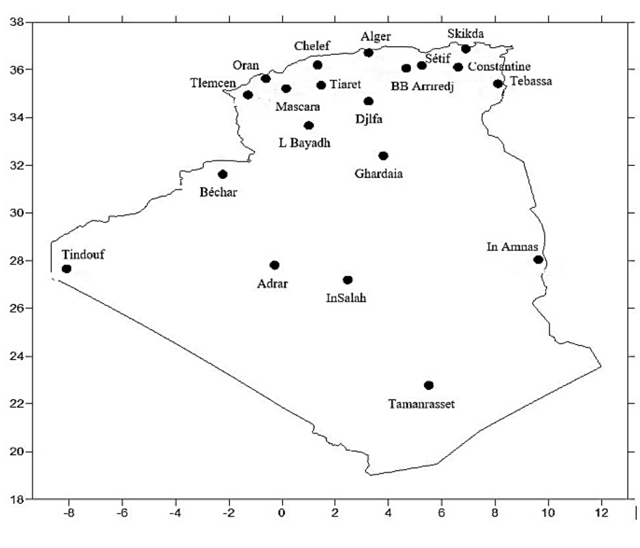


Figure 1. Position of the meteorological stations in Algeria [4]

Table 1. Geographical positions of the various regions under investigations [4, 12, 23]

	Sites	Longitude (°)	Latitude (°)	Altitude (m)	Topographic Situation
01	Skikda	06° 57' E	36°52'N	9	Coastal zone
02	Algiers	03° 15' E	36° 43'N	25	
03	Oran	00°37' W	35° 38'N	99	
04	Tebassa	08°08'E	35° 26'N	816	North of the Tellien mountains
05	Chlef	01°21'E	36° 10'N	112	
06	Tlemcen	01°19'W	34° 56'N	810	
07	Djelfa	03° 15' E	34° 41'N	1144	Highlands
08	Tiaret	01° 20' E	35° 23'N	1023	
09	El Bayadh	01° 01' E	33° 41'N	1305	
10	In Amenas	09° 38' E	28° 38'N	562	Sahara
11	InSalah	02° 28' E	27° 12'N	243	
12	Tindouf	08°08' W	27° 40'N	402	
13	Adrar	00°17' W	27° 53'N	264	
14	Béchar	02°15' W	31° 38'N	806	
15	Ghardaia	03° 49' E	32° 23'N	450	
16	Tamanrasset	05° 31' E	22° 47'N	1378	

The following classification in obtained based on the analysis of the sites altitude:

- 1st Gpoup ($H \leq 100$ m): Constantine, Ghardaïa, In Amenas, Mascara, Tindouf, and Tlemcen.
- 2nd Gpoup ($100 \leq H < 400$ m): Algiers, Oran, and Skikda.
- 3rd Gpoup ($400 \leq H < 700$ m): Adrar, Chlef, and In-Salah.
- 4th Gpoup ($700 \leq H < 1000$ m): Bechar, B.B Arriredj, Tebassa, and Tiaret.
- 5th Gpoup ($H \geq 1000$ m): Djelfa, El Bayadh, Setif, and Tamanrasset.

For the studied sites, the altitude above the sea level changes between 9 m in Skikda and 1378 m in Tamanrasset.

3. MATHEMATICAL TOOLS

3.1 Weibull technique

The distribution of wind velocity is usually modelled by the Weibull distribution model [24, 25]:

$$f(V) = \left(\frac{k}{c}\right) \cdot \left(\frac{V}{c}\right)^{k-1} \cdot \exp\left[-\left(\frac{V}{c}\right)\right]^{k} \tag{1}$$

for ($k > 0$, $V > 0$, $c > 1$).
where v: wind velocity, k: shape factor, c: Weibull scale factor.
The cumulative density is:

$$F(V) = \int_0^{\alpha} f(V).dV = 1 - e^{-\left(\frac{V}{C}\right)^{k}} \tag{2}$$

This function may be utilized to determine the time for which the wind is within a certain range of velocity (v_1 and v_2) [26]:

$$P(v_1 \prec v \prec v_2) = F(v_2) - F(v_1) \tag{3}$$

$$P(v_1 \prec v \prec v_2) = \exp\left(-\left(\frac{v_1}{c}\right)^{k}\right) - \exp\left(-\left(\frac{v_2}{c}\right)^{k}\right) \tag{4}$$

The probability for the wind exceeding V_x in its speed is [27, 28]:

$$P(v \geq v_x) = 1 - \left[1 - \exp\left(-\left(\frac{v_x}{c}\right)^{k}\right)\right] = \exp\left(-\left(\frac{v_x}{c}\right)^{k}\right) \tag{5}$$

The mean wind velocity (Vm) is [27, 28]:

$$V_m = \int_0^{\infty} f(V) \cdot dV = c \cdot \Gamma\left(1 + \frac{1}{k}\right) \tag{6}$$

The most frequent wind speed (V_E) is [27-30]:

$$V_E = c \cdot \left(1 + \frac{2}{k}\right)^{\frac{1}{k}} \tag{7}$$

The wind speed carrying maximum energy is [27-30]:

$$V_F = c \cdot \left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \tag{8}$$

The variance σ_2 of the data is [27, 30]

$$\sigma^2 = \int_0^{\infty} (V - \prec V \succ) \cdot f(V) \cdot dV = c^2 \cdot \left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right] \tag{9}$$

The standard-deviation of σ is then described as [27-30]:

$$Stadard\ \ deviation = \sqrt{Variance} \tag{10}$$

The average cubic velocity is [29, 30]:

$$\langle V^3 \rangle = \int_0^{\infty} V^3 \cdot P(V) \cdot dV = c^3 \cdot \Gamma\left(1 + \frac{3}{k}\right) \tag{11}$$

$$\Gamma(x) = \int_0^{\infty} \exp(-t) \cdot t^{x-1} \cdot dt \quad \text{with } x > 0 \tag{12}$$

3.2 Evaluation of the wind power

The power in moving air is the flow rate of kinetic energy per time [31]:

$$P = \frac{E}{t} = \frac{1/2.m.v^2}{t} \tag{13}$$

The density of wind power (P_d) is the power per unit area [31]:

$$P_d = \frac{P}{A} = \frac{1}{2}.\rho.v^3 \tag{14}$$

ρ_0: air density, (1.225 kg/m^3).
A: area swept by the rotor blades ($A = \pi.R^2$), [m^2].
Theoretically, the maximum power is [32, 33]:

$$P_{ext} = \frac{1}{2}.\ C_p(\lambda,\beta)\ \rho\ A.V^3 \tag{15}$$

C_p (λ, β): power coefficient, which is the aerodynamic performance of the wind turbine, where $C_{p\_max} = 0.59$, λ the speed ratio, and β the blade pitch angle.
The density of wind power E_{wdp} (kwh/m^2/year) is:

$$E_{wdp} = 3.1678.v^3 \tag{16}$$

According to [34-38], the power curve of a wind turbine may be determined as:

$$P(v) = \begin{cases} 0 & if \quad v \prec v_C \\ P_R\left(\dfrac{V^k - V_C^k}{V_R^k - V_C^k}\right) & if \quad v_C \le v \le v_R \\ P_R & if \quad v_R \le v \le v_F \\ 0 & if \quad v \succ v_F \end{cases} \tag{17}$$

P_R: rated electrical power;
v_C: the cut-in wind velocity;
v_R: rated wind velocity;
v_F: furling wind velocity; and
k: Weibull shape parameter.
The average power output is [29, 34, 39-41]:

$$P_{avrg} = \int_0^\infty P(v).f(v).dv = \int_{v_c}^{v_F} P(v).f(v).dv \tag{18}$$

$$P_{avrg} = \int_{v_C}^{v_R} P_R.\left(\frac{v^k - v_C^k}{v_R^k - v_C^k}\right).f(v).dv + \int_{v_R}^{v_F} P_R.f(v).dv \tag{19}$$

$$P_{avrg} = P_R\left(\frac{\exp\left[-\left(\frac{v_C}{c}\right)^k\right] - \exp\left[-\left(\frac{v_R}{c}\right)^k\right]}{\left(\frac{v_C}{c}\right)^k - \left(\frac{v_R}{c}\right)^k} - \exp\left[-\left(\frac{v_F}{c}\right)^k\right]\right) \tag{20}$$

P_{avrg} can be expressed as:

$$P_{avrg} = P_R.C_F \tag{21}$$

where, C_F is the capacity factor.

4. FINDINGS AND ANALYSIS

The statistical information of sites temperatures allowed the following classification:

- T < 16°C: Constantine, and B.B Arriredj;
- 16 ≤ T ≤ 21°C: Algiers, Tiaret, Tamanrasset, Skikda, Oran, Chlef, Tlemcen, Setif, El Bayadh, Djelfa, and Mascara; and
- 21°C ≤ T: Tebassa, Adrar, Bechar, Ghardaïa, In Salah, In Amenas, and Tindouf.

Table 2 summarizes the calculated Weibull parameters (*k*, *c*) and different velocities V_m, V^3, σ^2, V_E, V_F for various sites at 10 m height. Besides, Tables 3 and 4 present the calculated parameters at 30 m and 50 m, respectively, by using the methods of vertical extrapolation of Weibull parameters and wind.

Table 2. Details on the Weibull distribution and velocities for various sites at 10 m height

N°	Sites	k (-)	c (m/s)	V_m (m/s)	<V^3> (m/s)^3	σ^2 (-)	V_E (m/s)	V_F (m/s)
01	Skikda	1.57	3.30	2.96	066.30	11.31	3.36	5.57
02	Algiers	2.03	5.00	4.43	163.62	13.10	3.62	7.01
03	Oran	1.26	4.10	3.81	201.34	34.58	5.88	8.72
04	Tebessa	1.55	4.10	3.69	129.98	18.11	4.26	7.00
05	Chlef	1.82	4.50	4.00	135.17	14.04	3.75	6.76
06	Tlemcen	2.12	4.70	4.16	130.25	10.39	3.22	6.43
07	Djelfa	1.71	4.40	3.92	137.50	15.85	3.98	6.92
08	Tiaret	1.74	6.30	5.61	393.80	31.00	5.57	9.78
09	El Bayadh	1.62	5.30	4.75	260.86	26.69	5.17	8.71
10	In Amenas [4]	1.87	5.40	4.79	225.84	18.84	4.34	7.97
11	InSalah [4]	1.68	5.80	5.18	323.21	28.90	5.38	9.25
12	Tindouf [4]	1.90	5.40	4.79	221.61	18.08	4.25	7.88
13	Adrar [4]	2.15	7.20	6.38	462.23	23.54	4.85	9.78
14	Béchar [4]	1.35	4.80	4.40	274.11	37.73	6.14	9.41
15	Ghardaia [4]	1.65	5.60	5.01	298.97	28.31	5.32	9.06
16	Tamanrasset [4]	1.46	4.00	3.62	134.72	20.55	4.53	7.22

Table 3. Details on the Weibull distribution and velocities for various sites at 30 m height

N°	Sites	k (-)	c (m/s)	V_m (m/s)	$<V^3>$ $(m/s)^3$	σ^2 (-)	V_E (m/s)	V_F (m/s)
01	Skikda	1.74	4.40	3.92	134.16	15.12	06.83	2.69
02	Algiers	2.25	6.41	5.68	313.58	16.69	08.50	4.94
03	Oran	1.39	5.36	4.89	358.15	42.90	10.18	2.15
04	Tebessa	1.71	5.36	4.78	248.56	23.52	08.43	3.21
05	Chlef	2.01	5.83	5.17	262.04	18.26	08.22	4.14
06	Tlemcen	2.34	6.06	5.37	256.89	13.56	07.89	4.78
07	Djelfa	1.89	5.71	5.07	263.64	20.49	08.37	3.83
08	Tiaret	1.92	7.90	7.01	685.51	37.66	11.46	5.39
09	El Bayadh	1.79	6.76	6.01	468.19	33.10	10.28	4.28
10	In Amenas [4]	2.07	6.87	6.09	416.19	23.55	09.52	4.99
11	InSalah [4]	1.86	7.33	6.51	568.54	35.19	10.85	4.84
12	Tindouf [4]	2.10	6.87	6.08	410.43	22.72	09.45	5.05
13	Adrar [4]	2.38	8.92	7.91	809.00	28.19	11.53	7.09
14	Béchar [4]	1.49	6.18	5.58	477.96	46.16	10.94	2.93
15	Ghardaia [4]	1.82	7.10	6.31	530.89	34.95	10.67	4.58
16	Tamanrasset [4]	1.61	5.24	4.70	254.62	26.54	08.65	2.87

Table 4. Details on the Weibull distribution and velocities for various sites at 50 m height

N°	Sites	k (-)	c (m/s)	V_m (m/s)	$<V^3>$ $(m/s)^3$	σ^2 (-)	V_E (m/s)	V_F (m/s)
01	Skikda	1.83	5.04	4.48	188.58	17.36	07.55	3.27
02	Algiers	2.36	7.21	6.39	429.89	18.80	09.35	5.71
03	Oran	1.47	6.08	5.50	466.92	46.52	10.91	2.80
04	Tebessa	1.80	6.08	5.41	338.16	26.38	09.21	3.87
05	Chlef	2.12	6.58	5.83	357.41	20.36	09.00	4.87
06	Tlemcen	2.47	6.83	6.06	353.86	15.11	08.68	5.54
07	Djelfa	1.99	6.46	5.73	360.28	22.99	09.16	4.55
08	Tiaret	2.03	8.79	7.79	888.97	40.48	12.32	6.29
09	El Bayadh	1.89	7.58	6.73	616.74	36.11	11.11	5.09
10	In Amenas [4]	2.18	7.70	6.82	558.41	26.02	10.38	5.81
11	InSalah [4]	1.96	8.19	7.26	746.34	38.40	11.73	5.69
12	Tindouf [4]	2.21	7.70	6.82	551.82	25.16	10.31	5.86
13	Adrar [4]	2.50	9.86	8.75	1056.17	30.58	12.47	8.04
14	Béchar [4]	1.57	6.96	6.25	622.03	50.29	11.74	3.65
15	Ghardaia [4]	1.92	7.94	7.04	695.98	38.05	11.52	5.41
16	Tamanrasset [4]	1.70	5.95	5.30	342.91	29.45	09.40	3.53

Table 5. Details on the annual-mean-wind-power distribution for various sites at 10, 30 and 50 m heights

N°	Sites	Groups	P_{10} (w/m^2)	P_{30} (w/m^2)	P_{50} (w/m^2)	P_{ext10} (w/m^2)	P_{ext30} (w/m^2)	P_{ext50} (w/m^2)	E_{wpd10} $(kwh/m^2/year)$	E_{wdp30} $(kwh/m^2/year)$	E_{wdp50} $(kwh/m^2/year)$
01	Skikda	**A**	040.61	082.17	115.51	023.96	048.48	068.15	0210.03	0424.98	0597.40
02	Algiers	**A**	100.22	192.07	263.31	059.13	113.32	155.35	0518.31	0993.38	1361.82
03	Oran	**B**	123.32	219.36	285.99	072.76	129.42	168.73	0637.80	1134.54	1479.11
04	Tebessa	**A**	079.61	152.25	207.12	046.97	089.83	122.20	0411.76	0787.41	1071.23
05	Chlef	**A**	082.79	160.50	218.91	048.85	094.69	129.16	0428.18	0830.10	1132.20
06	Tlemcen	**A**	079.78	157.34	216.74	047.07	092.83	127.88	0412.61	0813.77	1120.98
07	Djelfa	**A**	084.22	161.48	220.67	049.69	095.27	130.20	0435.57	0835.15	1141.30
08	Tiaret	**C**	241.20	419.88	544.49	142.31	247.73	321.25	1247.47	2171.58	2816.08
09	El Bayadh	**B**	159.78	286.77	377.75	094.27	169.19	222.88	0826.35	1483.14	1953.73
10	In Amenas [4]	**B**	138.33	254.92	342.03	081.61	150.40	201.80	0715.42	1318.41	1768.94
11	InSalah [4]	**C**	197.97	348.23	457.13	116.80	205.46	269.71	1023.88	1801.02	2364.26
12	Tindouf [4]	**B**	135.73	251.39	337.99	080.08	148.32	199.41	0702.01	1300.18	1748.06
13	Adrar [4]	**C**	283.12	495.52	646.91	167.04	292.35	381.67	1464.27	2562.77	3345.75
14	Béchar [4]	**C**	167.89	292.75	380.99	099.06	172.72	224.79	0868.34	1514.08	1970.47
15	Ghardaia [4]	**C**	183.12	325.17	426.29	108.04	191.85	251.51	0947.09	1681.76	2204.73
16	Tamanrasset [4]	**A**	082.51	155.95	210.03	048.68	092.01	123.92	0426.76	0806.59	1086.29

As remarked in Tables 2-4, the yearly Weibull shape parameter k is ranging from a minimum $k_{10} = 1.26$ and $k_{50} = 1.47$ at, respectively, 10 and 50 m of heights for the site of Oran, until maximum $k_{10} = 2.15$ and $k_{50} = 2.50$, respectively, at 10 and 50 m heights for the area of Adrar.

The yearly Weibull scale parameter is ranging from a minimum $c_{10} = 3.30$ m/s and $c_{50} = 3.04$ m/s at, respectively, 10 and 50 m heights for the site of Skikda, until a maximum $c_{10} = 7.20$ m/s and $c_{50} = 9.86$ m/s at, respectively, 10 and 50 m heights for the site of Adrar.

The lowest values of annual mean wind speed are found in Skikda ($V_{10} = 2.96$ m/s and $V_{50} = 4.48$ m/s), while the most significant amounts are observed in Adrar ($V_{10} = 6.38$ m/s and $V_{50} = 8.75$ m/s).

Table 5 summarizes the annual-mean-wind-power for the studied sites at 10, 30, and 50 m of height. From this table, the highest values of annual mean wind speed and the annual mean wind power density are found in Adrar (P_{10} = 283.12 W/m^2 and P_{50} = 646.91 W/m^2), while the lowest values are observed in Skikda (P_{10} = 40.61 W/m^2 and P_{50} = 115.51 W/m^2, respectively).

Figure 2 presents a classification of the studied Algerian sites from the lowest to the highest average wind speeds. Besides, Figure 3 shows the calculated annual wind energy for the reviewed Algerian sites and is classified into three groups.

Figures 4 and 5 reveal a significant change in the seasonal average values of temperature and wind velocity, respectively, from one season to another and from a site to other.

Figures 6 and 7 present the maps of the wind resource and wind power density, respectively. A global view on the resources of wind energy in Algeria is provided in these figures. Besides, the regions where a significant resource of wind may exist are clearly indicated. These maps are really useful for the users of this kind of energies.

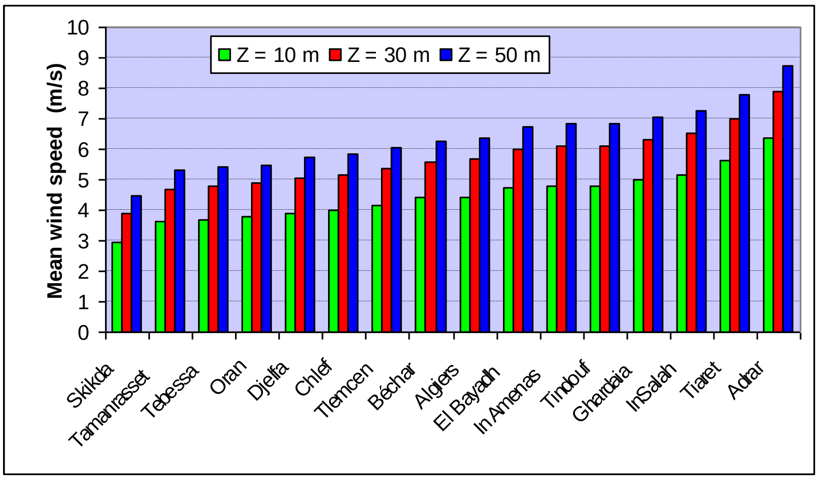


Figure 2. Mean velocity of the wind for various sites

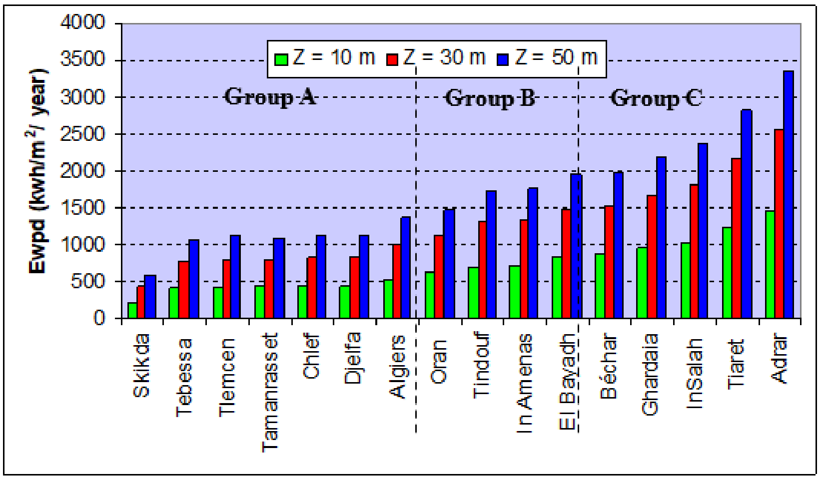
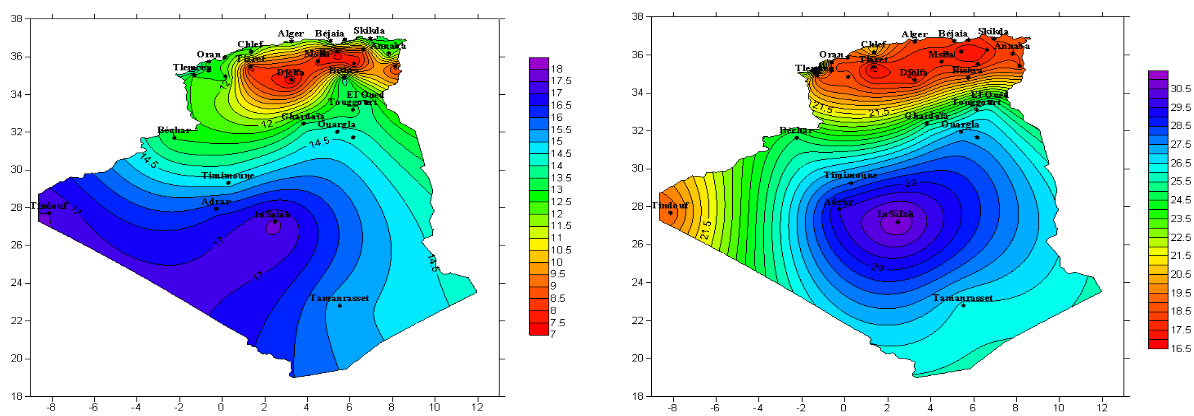
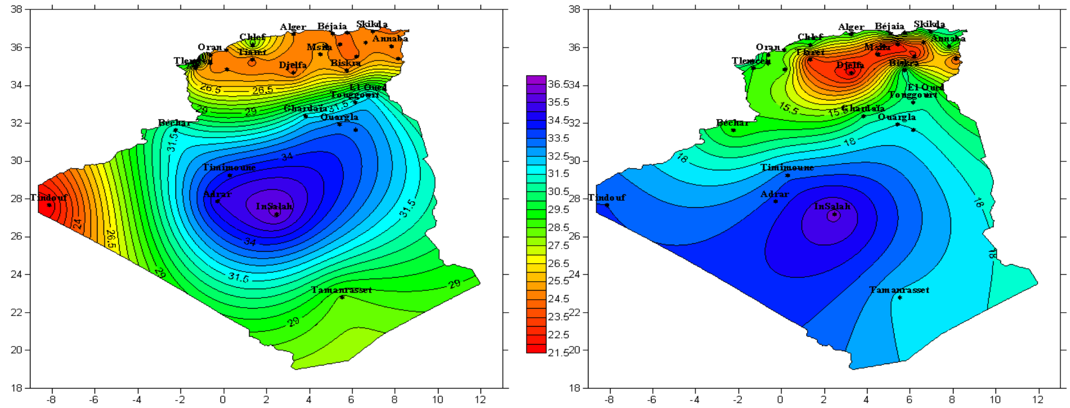


Figure 3. Annual wind energy for the various groups

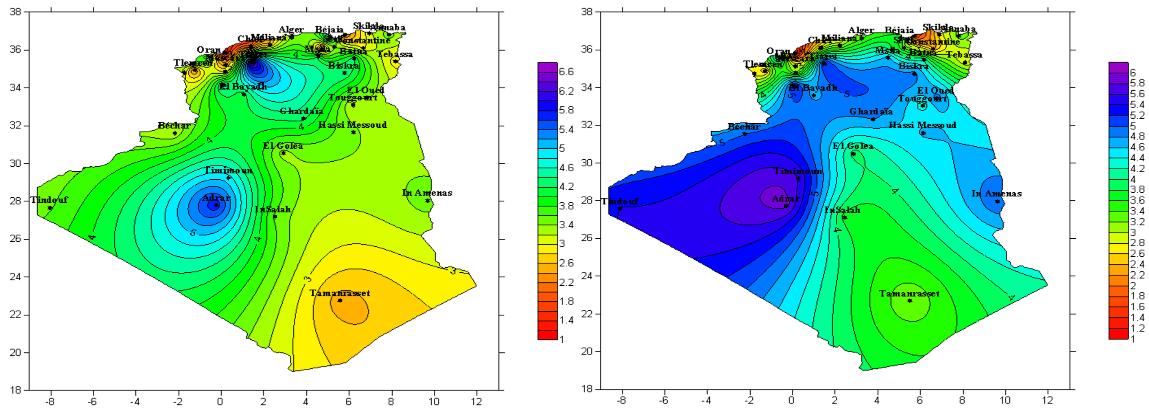


(a) Winter **(b)** Spring

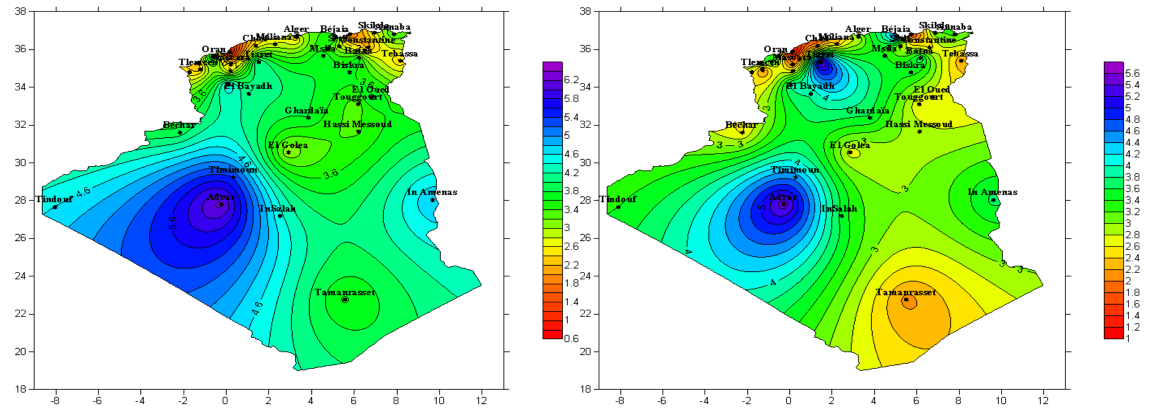


(c) Summer **(d)** Autumn

Figures 4. Seasonal average temperature over the Algerian territory

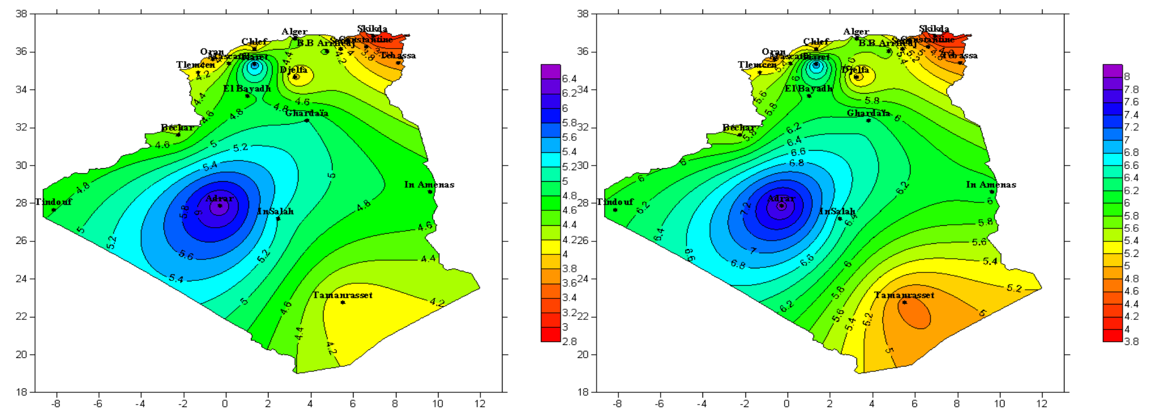


(a) Winter **(b)** Spring

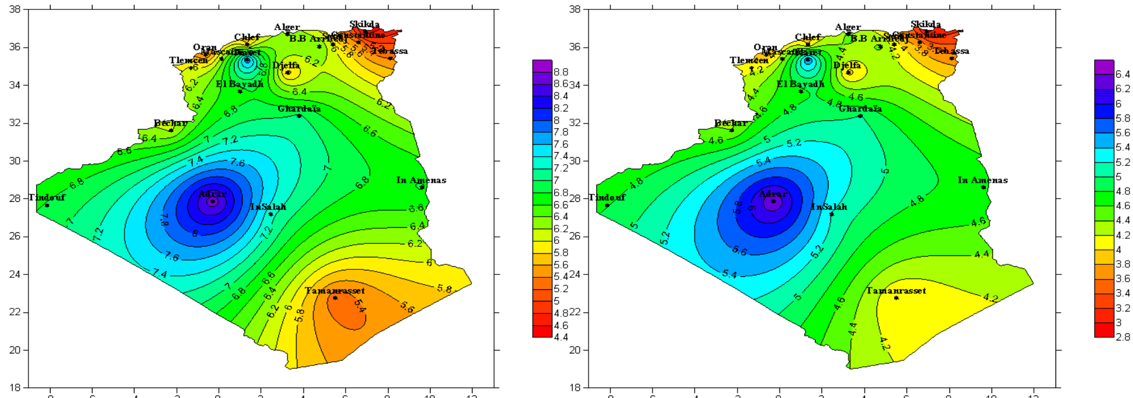


(c) Summer **(d)** Autumn

Figure 5. Seasonal average wind speed over the Algerian territory

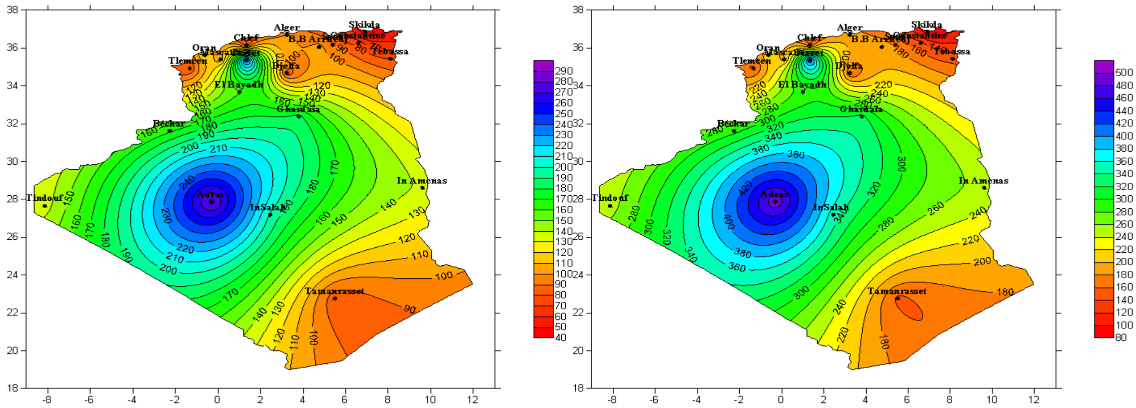


(a) At 10 m height **(b)** At 30 m height

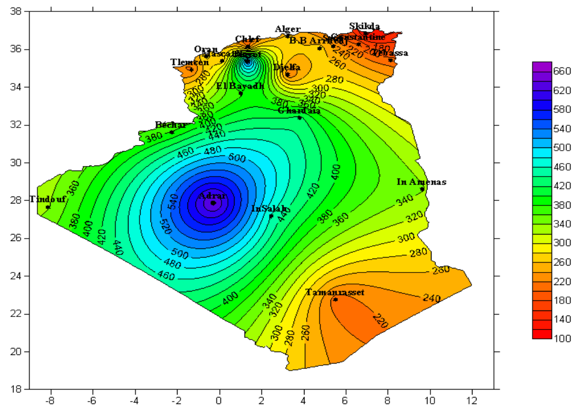


(c) At 50 m height **(d)** At 10 m height

Figure 6. Plot of the mean velocity of wind in Algeria, Vm at 10 m of height



(a) At 10 m height **(b)** At 30 m height



(c) At 50 m height

Figure 7. Plot of the power density of wind in Algeria, Vm at 10 m of height

The analysis of the results in Figures 6 and 7 (for example at 10 m height) allowed the following classification:

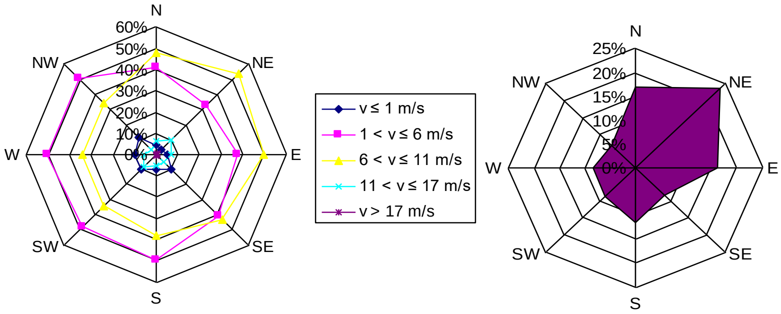
- **Group A**, including Algiers, Skikda, Tébessa, Chlef, Tlemcen, Djelfa and Tamanrasset, with an annual wind power ranging in $40.61 \leq P_{10} \leq 100.22$ W/m^2. The regions of this group are suitable for installation with low power, such as the water pumping.
- **Group B,** including, Oran, El Bayadh, In Amenas and Tindouf, with an annual wind power between $123.32 \leq P_{10} \leq 159.78$ w/m^2. These regions are characterized by an excellent potential of wind.
- **Group C,** including Tiaret, In Salah, Adrar, Béchar and Ghardaïa, has annual mean specific wind power: $167.89 \leq P_{10} \leq 283.12$ w/m^2. This group has very good to excellent wind potential (for wind farms and electricity production).

At the height of 10 m, the shape factor k is changing from 1.26 (at Oran) to 2.15 (at Adrar). While the scale factor c is changing from 3.30 m/s (at Skikda) to 7.20 m/s (at Adrar). The most significant amounts of the annual wind velocity and power density are observed in Adrar ($V_m = 6.38$ m/s and $P_{10} = 283.12$ W/m^2). However, the lowest amounts are observed in Skikda ($V_m = 2.96$ m/s and $P_{10} = 40.61$ W/m^2, respectively).

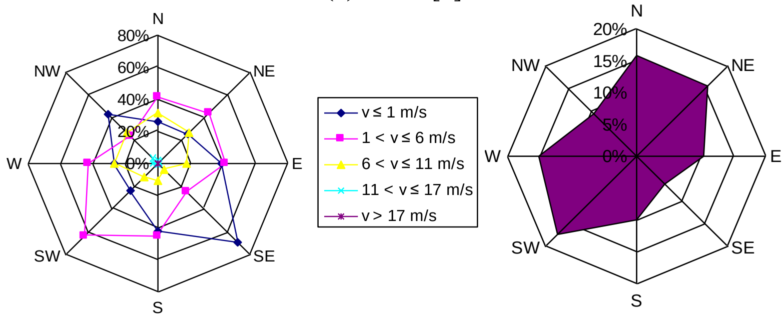
Figure 8 presents the wind rose for four sites located in different regions in Algeria.

The study of statistical information of the wind direction allowed the following classification:

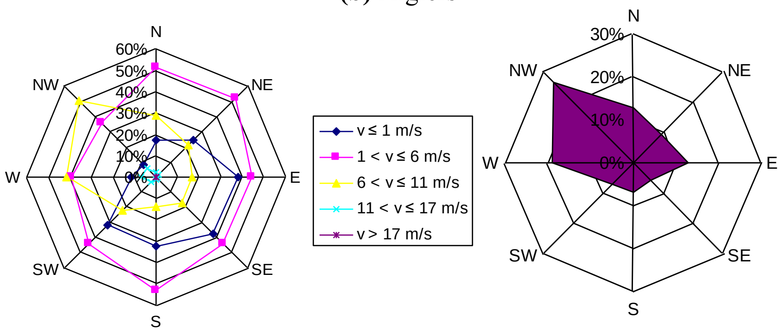
- Group 1 West W: Chlef, In Amenas, In Salah, Tebassa and Tiaret.



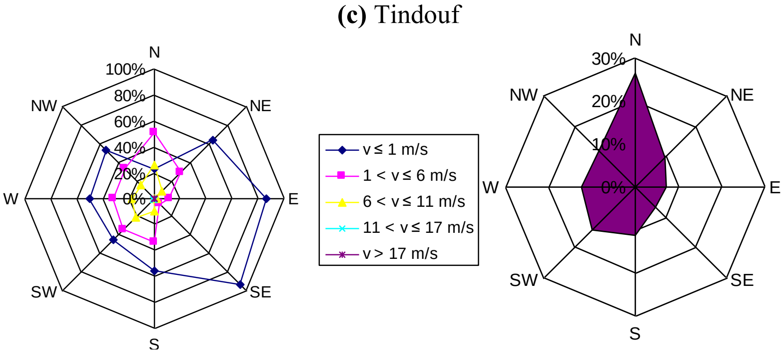
(a) Adrar [4]



(b) Algiers



(c) Tindouf



(d) Tlemcen

Figure 8. Charts of wind roses for various regions

- Group 2 North N: El Bayadh, Skikda and Tlemcen.
- Group 3 East E: Tamanrasset.
- Group 4 North-West: Djelfa, Ghardaïa and Tindouf.
- Group 5 North -East: Adrar and Oran.
- Group 6 South-West: Algiers and Béchar.

The wind rose analysis showed that the dominant wind directions for the studied sites are the North and the West (Figure 8). Other power systems [42-51] may be integrated in the future.

5. CONCLUSION

The wind resources of sixteen Algerian sites were determined in this paper. The annual average values of wind-velocity and power density were provided for each site. The main findings are summarized as follows:

- The yearly Weibull shape parameter k is ranging from a minimum $k_{10} = 1.26$ and $k_{50} = 1.47$ at, respectively, 10 and 50 m of heights for the site of Oran, until maximum $k_{10} = 2.15$ and $k_{50} = 2.50$, respectively, at 10 and 50 m heights for the area of Adrar.
- The yearly Weibull scale parameter is ranging from a minimum $c_{10} = 3.30$ m/s and $c_{50} = 3.04$ m/s at, respectively, 10 and 50 m heights for the site of Skikda, until a maximum $c_{10} = 7.20$ m/s and $c_{50} = 9.86$ m/s at, respectively, 10 and 50 m heights for the site of Adrar.
- The lowest values of annual mean wind speed are found in Skikda ($V_{10} = 2.96$ m/s and $V_{50} = 4.48$ m/s), while the most significant amounts are observed in Adrar ($V_{10} = 6.38$ m/s

and V_{50} = 8.75 m/s).

- The highest values of annual mean wind speed and the annual mean wind power density are found in Adrar (P_{10} = 283.12 W/m^2 and P_{50} = 646.91 W/m^2), while the lowest values are observed in Skikda (P_{10} = 40.61 W/m^2 and P_{50} = 115.51 W/m^2, respectively).
- A significant change in the seasonal average wind velocity and temperature from a season to another and a site to another.
- The most dominant wind directions for the studied sites were North and the West.
- The regions of group A are the suitable for wind applications with low power, like the water pumping and electricity production through small turbines. However, the regions of groups B and C are suitable for the application with high power.

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