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Risk assessment

EFFECT OF WIND TURBULENCE ON AEOLIAN ENERGY POTENTIAL

G. BANDOC[a]*, M. DEGERATU[b], E. DRAGOMIR[a]

[a]*Department of Meteorology and Hydrology, Centre for Coastal Research and Environmental Protection, University of Bucharest, 1 Nicolae Balcescu Blvd., District 1, 010 041 Bucharest, Romania*
E-mail: *geobandoc@yahoo.com*; *bandoc@geo.unibuc.ro*
[b]*Full Member of the Academy of Romanian Scientists, Technical University of Civil Engineering Bucharest, 124 Lacul Tei Blvd., Sector 2, 020 396 Bucharest, Romania*

Abstract. This paper aims to highlight the influence of wind turbulence on wind power potential. In order to achieve this objective the energy flow rate is computed as the ratio of the average flow to the energy flow based on average speed calculated for averaging time values that correspond to weeks, months, seasons, semesters and one year. In other words, the energy flow rate is determined on different turbulence macro-scales. The paper highlights the influence of wind turbulence on energy potential increase. The originality of this study lies in the fact that simple engineering calculations do not take into account the influence of turbulence on wind power potential. From the results we obtained, the following conclusions can be drawn: the maximum average speed depends on the averaging time, the higher the speed the lower the averaging time which is consistent with the theory; power flow coefficients *C* are all > 1 which leads to the conclusion that the average energy flow is greater than the energy flow computed using the average speed for the averaging times values used in the study (day, week, month, season, semester, year), i.e. turbulence macro-scales (with averaging times greater than 12 h according to as Van de Hoven) $(\overline{C})_{year}$, $[(\overline{C}_{day})_{day}$, $(\overline{C}_{week})_{year}$, $(\overline{C}_{month})_{year}$, $(\overline{C}_{season})_{year}$, $(\overline{C}_{semester})_{year}]$, the coefficients have values that range between (3.13 ... 1.93) which is consistent with the theory; it should be noted that the available measurements only allowed an analysis of the macroturbulences influence has the greatest contribution to the increase in the annual wind energy potential, much higher than the contribution of the winds microturbulence as the latter coefficients are considerably smaller.

Keywords: wind, macroturbulence, aeolian energy potential.

AIMS AND BACKGROUND

Natural wind, for a given average time of its local velocity, can be different local adimensional turbulence intensities, i.e. by different root-mean-square speed pulse values the RMS speed[1–4]. When computing wind energy potential the annual average energy flow plays a particularly important role. The sampling time is influenced by the wind speed, and consequently by averaging time[5–11].

[*] For correspondence.

If T is the averaging time, the time average local wind speed can be written as:

$$\overline{U} = \frac{1}{T}\int_0^T U(t)\mathrm{d}t, \tag{1}$$

where U is the instant local velocity which is equal to the sum of the average local speed and the pulsation speed as follows:

$$U = \overline{U} + U' \tag{2}$$

It should be noted that the average temporal pulse velocity is 0, i.e.:

$$\overline{U}' = \frac{1}{T}\int_0^T U'(t)\mathrm{d}t = 0 \tag{3}$$

because speed pulses are either positive or negative around the average U value.

Therefore, in order to determine the average pulse velocity in time interval T the root-mean-square is used, i.e. the RMS velocity:

$$U_{\mathrm{RMS}} = (\overline{U'^2})^{1/2} \tag{4}$$

which shows the average pulse velocity. Dividing RMS velocity by average speed, the local turbulence intensity is obtained:

$$I = U_{\mathrm{RMS}}/\overline{U} = (\overline{U'^2})^{1/2}/\overline{U} \tag{5}$$

which expresses the average value of the pulsation speeds in relation to the average speed both of which are local and computed for the same averaging time T.

Given that pulse speed is the difference between instantaneous speed and average speed:

$$U' = U - \overline{U} \tag{6}$$

and by substituting the expression (6), in equation (3) of the pulse temporal average speed $\overline{U}'$, the following relationship is obtained:

$$\overline{U} = \frac{1}{T}\int_0^T \left(U - \overline{U}\right)\mathrm{d}t = 0 \tag{7}$$

The average energy flow for the same time period T is proportional to the $\overline{U^3}$ and considering equation (2) has the expression:

$$\overline{U^3} = \frac{1}{T}\int_0^T \left(\overline{U} + U'\right)^3 \mathrm{d}t = \overline{U}^3 + 3\overline{U}^2 \cdot \overline{U'} + 3\overline{U} \cdot \overline{U'^2} + \overline{U'^3} \tag{8}$$

As $\overline{U'} = 0$, and because $3\overline{U}\,\overline{U'^2} \neq 0$ for $\overline{U'^2} \neq 0$ and given that $\overline{U'^3} \neq 0$ only if the probability distribution of U' is symmetrical, equation (8) becomes:

$$\overline{U^3} = \overline{U}^3 \left(1 + 3\frac{\overline{U'^2}}{\overline{U}^2} + \frac{\overline{U'^3}}{\overline{U}^3} \right) \tag{9}$$

By determining the ratio of the average energy flux $\overline{U^3}$ and the power flow computed using the average speed $\overline{U}^3$, the following equation is obtained:

$$\frac{\overline{U^3}}{\overline{U}^3} = 1 + 3\frac{\overline{U'^2}}{\overline{U}^2} + \frac{\overline{U'^3}}{\overline{U}^3} \tag{10}$$

where $\overline{U'^2}/\overline{U}^2$ is the turbulent intensity I.

This energy flow ratio can be noted as coefficient C, i.e.:

$$C = \overline{U^3}/\overline{U}^3 = 1 + 3I^2 + \overline{U'^3}/\overline{U}^3 \tag{11}$$

where the last two terms represent the contribution of turbulence to the size of the average energy flow. The energy flow ratio expressed as the coefficient C strongly depends on strong integration time T, i.e. on the averaging time[12].

RESULTS AND DISCUSSION

This paper used complex data that consisted of a large number of wind speed measurements made over one year, every 6 h. For a comprehensive analysis in terms of climatic characteristics it can be used remote sensing and GIS technologies.

Firstly, the distribution of the velocity U considered to be instantaneous was plotted in Fig. 1, but computed as a temporal average over a time period equal to the averaging time of the employed anemometer and with a 6-hour sampling period. The energy flow U^3 was computed and its distribution throughout the year was plotted as well (Fig. 2).

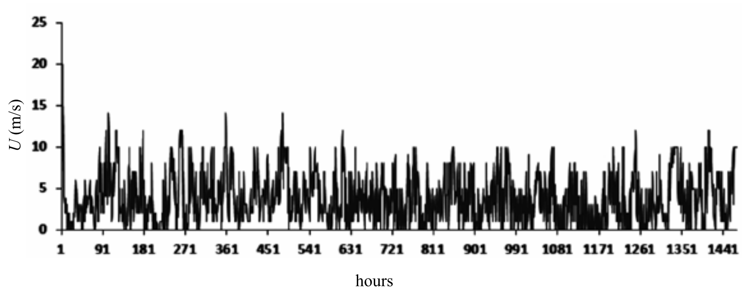

Fig. 1. Instantaneous speed distribution throughout the year

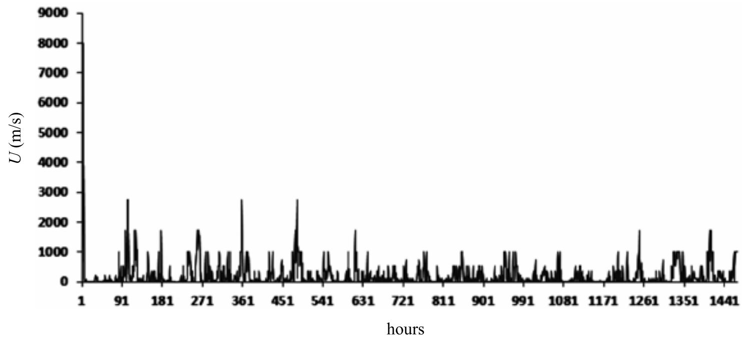

Fig. 2. Distribution of energy flow throughout the year

For the entire data set, we determined the two flows of energy $\overline{U}^3$ and $\overline{U^3}$ for different averaging times T, i.e. days ($\overline{U}_{day}{}^3$, $\overline{U_{day}{}^3}$) (Fig. 3), weeks ($\overline{U}_{week}{}^3$, $\overline{U_{week}{}^3}$) (Fig. 4), months ($\overline{U}_{month}{}^3$, $\overline{U_{month}{}^3}$) (Fig. 5), seasons ($\overline{U}_{season}{}^3$, $\overline{U_{season}{}^3}$) (Fig. 6) semesters ($\overline{U}_{semester}{}^3$, $\overline{U_{semester}{}^3}$) (Fig. 7) and for the whole year ($\overline{U}_{year}{}^3$, $\overline{U_{year}{}^3}$) (Fig. 8).

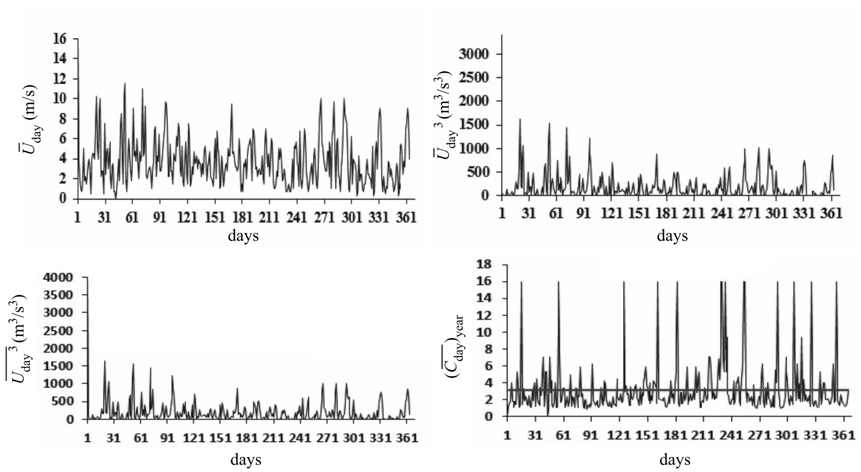

Fig. 3. Distribution of $\overline{U}_{day}$, $\overline{U}_{day}{}^3$, $\overline{U_{day}{}^3}$ throughout the year and the annual average value $(\overline{C}_{day})_{year}$

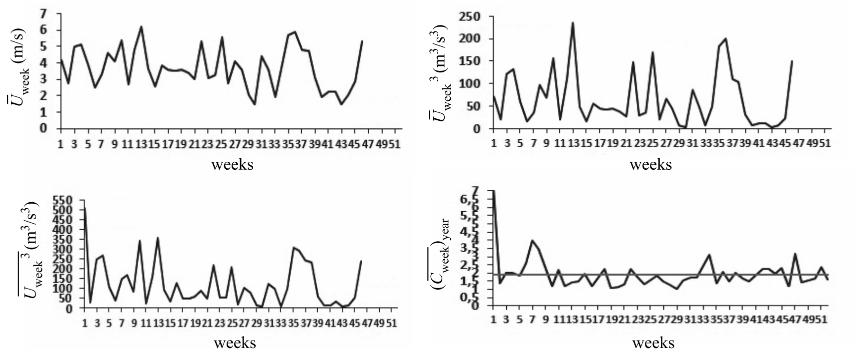

Fig. 4. Distribution of $\overline{U}_{\text{week}}$, $\overline{U}_{\text{week}}{}^{3}$, $\overline{U_{\text{week}}{}^{3}}$ throughout the year and the annual average value $(\overline{C}_{\text{week}})_{\text{year}}$

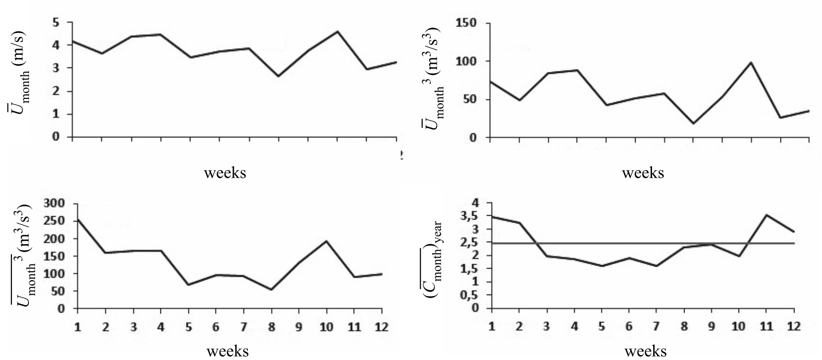

Fig. 5. Distribution of $\overline{U}_{\text{month}}$, $\overline{U}_{\text{month}}{}^{3}$, $\overline{U_{\text{month}}{}^{3}}$ throughout the year and the annual average value $(\overline{C}_{\text{month}})_{\text{year}}$

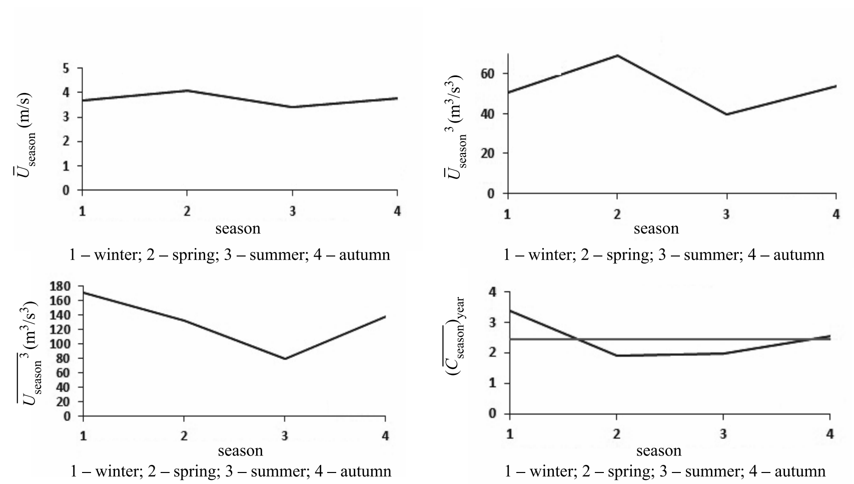

Fig. 6. Distribution of $\overline{U}_{\text{season}}$, $\overline{U}_{\text{season}}{}^{3}$, $\overline{U_{\text{season}}{}^{3}}$ throughout the year and the annual average value $(\overline{C}_{\text{season}})_{\text{year}}$

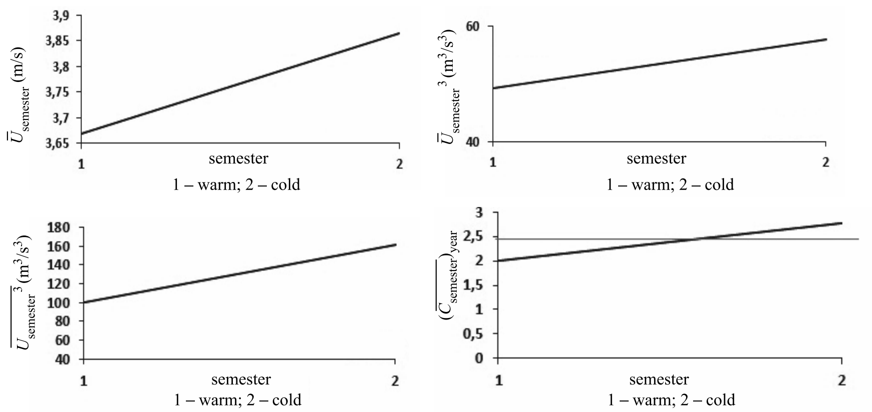

Fig. 7. Distributions of $\overline{U}_{semester}$, $\overline{U}_{semester}{}^3$, $\overline{U_{semester}{}^3}$ throughout the year and the annual average value $(\overline{C}_{semester})_{year}$

C coefficients were determined for each day, week, month, season, semester and year as the ratio of energy, after which these coefficients average value were determined for the entire year, as follows:

– for the days: $C_{day} = \overline{U_{day}{}^3}/\overline{U}_{day}{}^3$ and $(\overline{C}_{day})_{year}$;

– for weeks: $C_{week} = \overline{U_{week}{}^3}/\overline{U}_{week}{}^3$ and $(\overline{C}_{week})_{year}$;

– for months: $C_{month} = \overline{U_{month}{}^3}/\overline{U}_{month}{}^3$ and $(\overline{C}_{month})_{year}$;

– for seasons: $C_{season} = \overline{U_{season}{}^3}/\overline{U}_{season}{}^3$ and $(\overline{C}_{season})_{year}$;

– for semesters: $C_{semester} = \overline{U_{semester}{}^3}/\overline{U}_{semester}{}^3$ and $(\overline{C}_{semester})_{year}$

– for the entire year: $C_{year} = \overline{U_{year}{}^3}/\overline{U}_{year}{}^3$ and $(\overline{C}_{an})_{an} = C_{an}$.

Based on these calculations distributions over the entire year plotted, for $\overline{U}$, for $\overline{U}^3$, for $\overline{U^3}$ and for *C*, while also marking the annual average values of coefficient, $(C)_{year}$, i.e. [$\overline{U}_{day}$, $\overline{U}_{day}{}^3$, $\overline{U_{day}{}^3}$, $(\overline{C}_{day})_{year}$] for days (Fig. 3), [$\overline{U}_{week}$, $\overline{U}_{week}{}^3$, $\overline{U_{week}{}^3}$, $(\overline{C}_{week})_{year}$] for weeks (Fig. 4), [$\overline{U}_{month}$, $\overline{U}_{month}{}^3$, $\overline{U_{month}{}^3}$, $(\overline{C}_{month})_{year}$] for months (Fig. 5), [$\overline{U}_{season}$, $\overline{U}_{season}{}^3$, $\overline{U_{season}{}^3}$, $(\overline{C}_{season})_{year}$] for seasons (Fig. 6) and [$\overline{U}_{semester}$, $\overline{U}_{semesrer}{}^3$, $\overline{U_{semester}{}^3}$, $(\overline{C}_{semester})_{year}$] for semesters (Fig.7).

The maximum average speed is a function of averaging time *T*, and increases as the averaging time decreases which is consistent with the theory (Fig. 8).

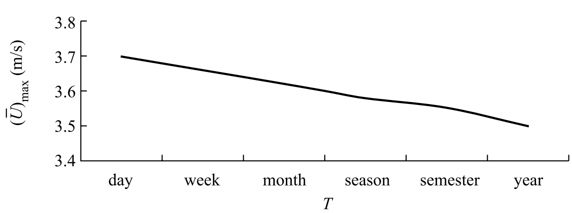

Fig. 8. Variation depending maximum average speed $(\overline{U})_{max}$ over averaging time *T*

All energy flow C coefficients are > 1 which leads to the conclusion that the average energy flow is greater than the energy flow computed using the average speed (Fig. 9).

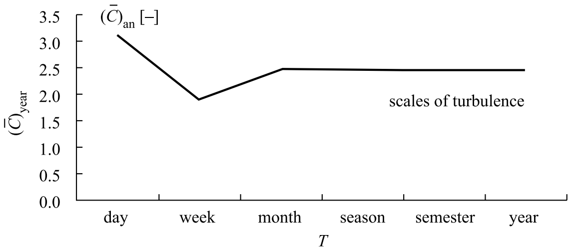

Fig. 9. Variation of energy flux coefficients annual average values $(\overline{C})_{year}$ depending on averaging time T

CONCLUSION

From the results we obtained, the following conclusions can be drawn:

– the maximum average speed $(\overline{U})_{max}$ is a function of averaging time T, and increases as the averaging time decreases whuch is consistent with the theory

– all energy flow C coefficients are > 1 which leads to the conclusion that the average energy flow is greater than the energy flow computed using the average speed ($\overline{U^3} > \overline{U}^3$; $C > 1$);

– for the considered averaging times (day, week, month, season, semester, year), i.e. turbulence macro-scales (with averaging time greater than 12 h, according to Van der Hoven), the coefficients $(\overline{C})_{year}$, $[(\overline{C_{day}})_{day}$, $(\overline{C_{week}})_{year}$, $(\overline{C_{month}})_{year}$, $(\overline{C_{season}})_{year}$, $(\overline{C_{semester}})_{year}]$ have values that range between (3.13 ... 1.93), which is consistent with the theory;

– it should be noted that the available measurements only allowed an analysis of the macroturbulence influence that has the greatest contribution to the increase of the annual wind energy potential which is much higher than the contribution of the wind microturbulence, as the latter $(\overline{C})_{year}$ coefficients are considerably smaller.

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