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WIND CONDITIONS MODELING FOR SMALL WIND TURBINES

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Wind energy systems are a solution which became cost effective by recent technological developments. Small wind turbines represent a solution for distributed generation systems including off grid systems for remote area. Due to the random nature of the wind and the unavailable wind data, modeling and simulation of wind conditions is a useful tool in defining the chosen technical solutions and preliminary evaluation of system performance. Mean wind speed at a site measured or evaluated in wind turbine hub height and determining the level of turbulent are important elements both in the choice of equipment and in setting energy performance and system reliability.

Keywords: wind turbine, wind assesment, mean wind speed, turbulence intensity

1. Introduction

Wind power is recognized as the closest commercialization of renewable energy technologies in the world. With the rapid wind power development, most of wind turbines have experienced operational failures, which directly affect the wind power safety and economy. Therefore, it is particularly important to make a correct evaluation of the wind characteristics and to adopt the proper solution of the wind turbine. In this paper, we describe how to properly model the wind conditions in order to obtain specific aspects of the wind, respectively the average speed value, turbulence intensity and turbulence duration.

2. Wind conditions modeling for the operation of small wind turbines

Regarding wind turbine operating conditions which influence the power and the loads can be defined two different modes, the normal and extreme modes both determined by local wind conditions.

Normal wind conditions occur in normal operation, extreme wind conditions are special conditions that have a recurrence period of 1 or 50 years.

The modeling of the wind conditions is based on the mean wind speed which represent the average of wind speed over a 10 minutes and which has a

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0.02 exceeding probability during an year of (which corresponds to the mean recurrence interval of 50 years) .

An equivalent wind model can include two modules, a deterministic module - for mean wind speed and periodic variations, and stochastic module (random) - to simulate turbulences [i].

Under these conditions, the wind is expressed in its specific aspects, respectively the average speed value, turbulence intensity and turbulence duration:

$$v(x,y,z,t) = u(x,y,z) + w(x,y,z,t) \tag{1}$$

where,

$v(x,y,z,t)$ the velocity vector, determined in time and space;

$u(x,y,z)$ the deterministic component of the wind speed;

$w(x,y,z,t)$ the stochastic component with zero average value;

From this point of view the wind speed and the turbulence regime represent the characteristics for sites and can be the basic parameters for wind turbines classes [ii].

Table 1

Classes of small wind turbines

Class	I	II	III	IV
The average speed at hub height [m/s]	10	8,5	7,5	6
Turbulence intensity at 15 m/s	0,18	0,18	0,18	0,18

The wind turbine power generation is defined by its power curve $P = P(v)$ estimated by the calculations and validated by testing and measurements.

Mean wind speed distribution in the location is important for determining the energy production and to define frequency of occurrence of the individual load conditions.

The average power generated by a wind turbine with a $P = P(v)$ power curve for a given average wind speed v_∞ is determined by the relation [iii]:

$$P_m(v_\infty) = \int_0^\infty Pr(v\ )\cdot P(v)dv \tag{2}$$

where, $Pr(v)$ represents the cumulative probability distribution of wind speed at turbine hub height.

Modeling normal wind conditions starts from the premise that there is a Rayleigh distribution of wind speeds measured at the turbine axis given by [iv]:

$$Pr(v_t) = 1 - exp\left[-\pi\left(\frac{v_t}{2v_{med}}\right)^2\right] \tag{3}$$

At the same time normal wind speed profile should be considered to be given by the power law [v]:

$$v(h) = v_t \left(\frac{h}{h_t} \right)^{\alpha} \tag{4}$$

The value of the exponent α for the power law shall be assumed to be 0, 2. In the stochastic simulation module of turbulent effects must be included the normal turbulence model, meaning random variations of wind velocity from the 10 minutes average which includes the effects of a variation of speed and direction.

The characteristic value of the standard deviation of the longitudinal component of the standard deviation of wind speed is given by [2]:

$$\sigma_1 = I_{15} \frac{(15 + a v_t)}{(a+1)} \tag{5}$$

where, $I_{15} = 18\%$ and $a = 2$.

Operation of wind power systems in terms of efficiency and safety depends on the adaptation of the wind turbine to local wind conditions.

By determining wind conditions will able to define the limits of use for small and medium wind turbines or will able to establish descriptive technical parameters of the turbine.

Simulation of the wind regime offers information on the operation of the wind turbine, both in terms of production and loads.

If we refer to the simulation of the operation of the wind turbine as a system of converting air kinetic energy into mechanical energy of rotation or the entire chain of electromechanical energy conversion in the wind power system, rated wind speed, mean wind speed from the location and rated wind turbine power are important parameters in this analysis.

3. The limits of variation of the annual mean wind speed

The determined or estimated average wind speed in a site provides preliminary information related to energy production, but it also is an element of analysis in selecting of an energy conversion solution using equipments with certain technical characteristics.

Based on the random character of wind speed, the purpose of the analysis presented below is related to definition the reference period in relation to the annual mean wind speed for the better wind assessment.

In this analysis the wind date is measured over a period of 7 years (2006 - 2012) in a location with significant wind potential in the shore area, Agigea locality, Constanta County, measuring point being located at 30 m height.

Table 2

The average monthly rate for the period 2006-2012 - Agigea location

	2006	2007	2008	2009	2010	2011	2012	Monthly average
	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
January	5,22	5,8	6,1	6,13	6,2	5,55	6,05	5,86
February	5,34	5,48	5,34	5,57	6,3	5,36	5,19	5,51
March	5,2	5,91	5,43	5,4	5,96	5,81	5,62	5,62
April	5,07	4,87	5,18	5,1	5,55	4,8	4,63	5,01
May	4,94	4,51	5,55	3,98	5,4	4,53	3,42	4,62
June	4,73	5,2	4,42	4,52	4,11	3,85	4,02	4,41
July	4,26	4,33	4,69	4,38	4,33	3,56	4,16	4,37
august	4,18	5,25	5,32	3,8	4,85	4,13	4,52	4,76
September	4,88	5,2	4,24	4,02	5,85	5,05	4,65	4,84
October	5,19	5,3	4,74	4,41	5,68	5,99	4,15	5,19
November	5,62	5,5	5,77	5,7	5,99	5,17	4,41	5,45
December	5,9	5,74	6,2	6,15	6,22	5,79	5,47	5,92
Annual mean wind speed	**5,04**	**5,26**	**5,25**	**4,93**	**5,54**	**4,97**	**4,69**	**5,10**
Mean speed for two years		**5,15**	**5,25**	**5,09**	**5,23**	**5,25**	**4,83**	**5,10**
Mean speed for three years	-	**-**	**5,18**	**5,14**	**5,23**	**5,14**	**5,06**	**5,10**

Measurements were performed at the ICPE Agigea - Test Site Facility and measurement configuration included:

- anemometers (three) different heights: 30, 20 and 10 m;
- wind vanes for wind direction (two) 30m and 15 m;
- temperature sensor;
- relative humidity sensor;
- pressure sensor;
- data acquisition system and GPRS data transmission;

The measuring campaign was between 2006 - 2012 and relating to the mean wind speed at $h = 30$m is given in Table 2.

Analyzing measured and collected data during this period is found that the average annual wind speed of the site in specified measurement point is 5.10 m/s. Can be noticed that the year less "productive" in this period was the 2012 with an annual mean wind speed of 4.69 m/s.

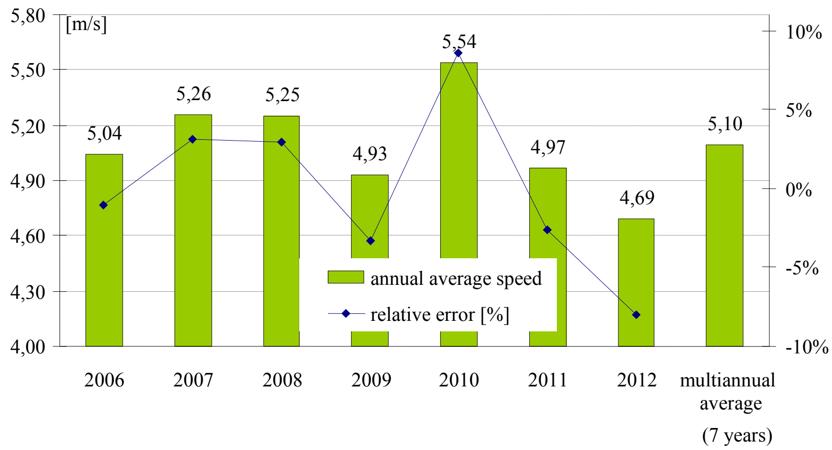

Fig. 1.1 Annual values of mean wind speed for the period 2006-2012

If we were considering that every year has been a period of reference in local assessment wind potential (annual measurement campaign), the annual mean wind speed are in the range between 4.69 m/s and 5.54 m/s.

According to the year in which measurements were made, the relative error rate of speed compared with the average speed measured during a seven years period is between -8% and 9%, which may lead to an error of estimation in energy with values between -30% and 33% (Fig. 1.1).

After calculating the average speed for each period considered and by comparison with the annual average value of the site it is found that the level of the relative error for wind speed is reduced to a range between 3% and 5% (a period of two consecutive years) (Fig. 1.2).

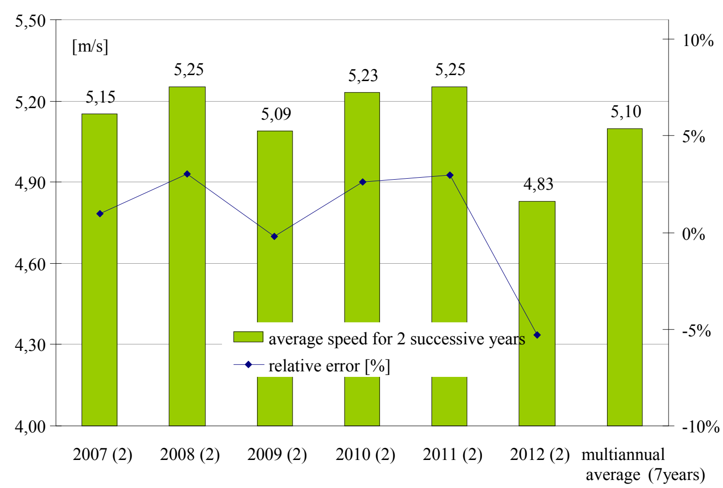

Fig. 1.2 Average speed values for a period of 2 consecutive years

A period of three consecutive years considered the reference period leads to an estimation of wind speed in satisfactory limits if we consider the estimated average speed of 5, 1 m/s, meaning that, in this case, the value of the relative error does not exceed 2-3%. (Fig. 1.3).

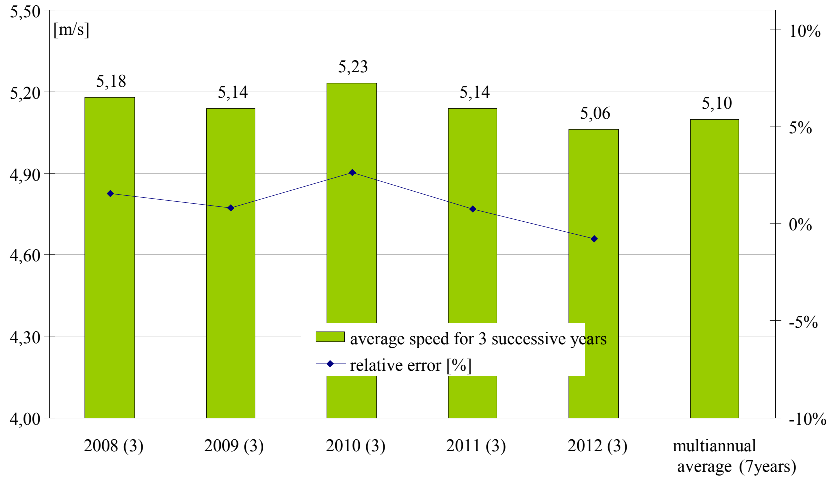

Fig. 1.3 Average speed values for a period of 3 consecutive years

There are a few cases where for the area of interest, in addition to the local wind measurements (STD – Short Term Data) also are available historical wind data provided by a weather station located close to measurement point[vi]. Using historical wind data measured on the long term (LTD – Long Term Data) may be possible if the wind data series meet the minimum specifications required by the analysis, such as:

1. there are available data for the period in which field measurements are made (STD)
2. there is correlation between data series during a common period;
3. existing LTD series shows an acceptable confidence level and the wind data are not compromised by the depreciation of the wind measurement systems, by moving or changing the configuration of equipment, or by occurrence of disturbance factors during measurement period (buildings, vegetation, etc.).

The process through which the data measured (STD) is analyzed in relation to the long-term data (LTD) set from the weather station, fact that enables an estimation of long-term data set for the specific location is called the Measure-Correlate-Predict method (MCP).

MCP method represents a mathematical model with three input parameters:

- reference wind data: long-term wind data (Ref – LTD);
- reference wind data: long-term measured data coincident with the site

- site data: field data of the location (Site-STD);

”Measure” procedure is used to make an analysis of the available wind data in the two time series in such a way that certain corrections may be made concerning:

- removal of inaccurate wind data (freezing equipment, data out of range, etc.);
- corrections concerning the measurement range and time into the databases;
- limiting the differences between measurement to eliminate the extreme values;

The”Correlate” procedure sets the correlation function between the two databases for the time period when STD measurements corresponding with LTD measurements.

The two statistical series have the form (v_{med}, dir_{med}), a statistical pair, site-specific, and is analyzed the relation that describes the link between the two statistical series.

Statistical relevancy of the determination of correlation coefficient is dependent on the presence of a normal distribution for at least one of data series so that the influence between the two variables is obvious.

Although conditions are different (average values at 10 minutes and hourly average values, different measurement heights for the two time series, etc.) considering that in both cases the measurements are not affected by errors of the method, the positive regression coefficient is above 0,3.

For a satisfactory analysis the values must be in the range 0,75-1,0. It is also calculated the standard deviation for wind speed and energy, and the corresponding average values. Regression equations are not required to be linear, most often polynomial functions describe the phenomena in the best possible way.

Generically called ”PREDICT” procedure, allows the calculation of regression coefficients knowing the average values and standard deviations based on the correlation coefficient between the two series.

Setting the reference period for conducting a measurements campaign devoted to assessing the wind potential is dependent on meteorological factors (location, local and regional conditions, seasonal variations, etc.), technical factors (ensuring the good functioning of monitoring equipment, calibration, preventive and corrective maintenance) as well as legal or financial factors related to project progress.

Analyzing the aspects above which were made on a relatively long period of time it can be concluded that a minimum of one year of wind potential measurements can provide useful informations, but can lead to wrong decisions. Depending on the importance of the project, a three years period to conduct short-term measurements will lead to the diminishing of the the relative error of the measured values, thus increasing the predictability.

Making a measurement campaign extended to three consecutive years will introduce additional technical requirements that must be provided, particularly related to the selection of measurement equipments in order to maintain operating parameters within defined limits.

4. The turbulence regime

The effects of turbulence are due to unstable atmospheric conditions that manifest more pronounced at low wind speeds. The wind turbulence denotes stochastic variations in the wind speed during 10 minutes average and includes the effects of varying wind speed, varying direction and rotational sampling.

Simulation of the turbulent regime model aims the validation of the vertical wind profile and distribution on each interval of the average velocity, turbulence intensity of the point of interest in order to define the environmental conditions of the site [vii].

Data analysis is measured at Râmnicu Sărat location (table 3), measured data covering a period of 730 days during July 2009 - August 2011.

Table 3

Synthetic data from Râmnicu Sărat location

Measurement Point	Height	Mean wind speed	Standard deviation	Turbulence intensity
	[m]	[m/s]	[m/s]	[-]
	60	5,76	0,52	0,09
	50	5,59	0,56	0,1
	40	5,39	0,59	0,11

For each measurement point were measured and calculated speed average and standard deviation by averaging a 10 minute interval. Turbulence intensity was calculated both overall and for each speed interval in Table 4.

Table 4

Distribution of turbulence level for speed intervals

Range	Speed range	Turbulence intensity		
	[m/s]	60 m	50 m	40m
0	0.... 0,49	-	-	-
1	0,5.....1,49	-	-	-
2	1,5.....2,49	-	-	-
3	2,5.....3,49	-	-	-
4	3,5.....4,49	0,12	0,13	0,13
5	4,5.....5,49	0,11	0,11	0,12
6	5,5.....6,49	0,10	0,10	0,10
7	6,5.....7,49	0,09	0,09	0,09
8	7,5.....8,49	0,08	0,09	0,09
9	8,5.....9,49	0,08	0,09	0,09
10	9,5...10,49	0,08	0,09	0,09
11	10,5....11,49	0,08	0,10	0,09
12	11,5...12,49	0,08	0,10	0,09
13	12,5...13,49	0,08	0,10	0,09
14	13,5...14,49	0,09	0,10	0,09

15	14,5...15,49	0,09	0,10	0,10
16	15,5...16,49	0,09	0,11	0,10
17	16,5...17,49	0,10	0,11	0,10
18	17,5...18,49	0,11	0,10	0,10
19	18,5...19,49	0,10	0,10	-
20	19,5...20,49	-	-	-

Establishing the level of turbulence intensity involves vertical extrapolation of the measured data and determination of the values of turbulence intensity for the point of interest. The premises are related to the fact that under conditions of stationary flow is considered that the standard deviation of wind speed is the same for different heights.

$$\sigma(h_1) = \sigma(h_2) \tag{6}$$

It is important to validate the vertical profile of the wind model and to achieve this; the two calculation methodologies will be compared.

For an exponential variation of the vertical profile of wind speed at heights h_1 and h_2 is calculated using:

$$v(h_2) = v(h_1)\left(\frac{h_2}{h_1}\right)^{\alpha} \tag{7}$$

where α is the exponent of the vertical wind speed dependent on the roughness length of the terrain. For wind mast location with the roughness length estimated at 0,18 m was adopted the value $\alpha = 0{,}13$ [viii].

For the second method it was used the logarithmic law deduced from fluid flow in steady-state conditions, the expression is given by:

$$v_2(h_2) = \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \cdot v_1(h_1) \tag{8}$$

Vertical variation of wind speed is not calculated directly. However can be determined the average speed in relation to a reference height at which the wind speed was already measured (reference value).

In this case it was established the identical roughness length of 0, 18 . The results are shown in Table 5, where it was considered the reference value, the average velocity measured at 60 m height.

Table 5

Errors in estimating the vertical profile of wind

Measurement Point	Height	Mean wd speed	Exponential profile		Logarithmic profile	
		measured	speed	error	speed	error
	[m]	[m/s]	[m/s]	[%]	[m/s]	[%]
	60	5,76	5,76	0%	5,76	0%

	50	5,59	5,71	2,1%	5,58	0,2%
	40	5,39	5,43	0,7%	5,37	0,4%

At both levels of measurement (50 m and 40 m) the estimation error is less than 3% and for the logarithmic profile model the relative error is below 1.5%.

The logarithmic model of vertical wind profile approximates, with better accuracy, vertical variation of wind speed in the in conditions in which it can be defined the local configuration of the site.

Using logarithmic profile allows calculation of turbulence intensity in the points was was not actually performed measurements.

Based on the definition of turbulence intensity can be established standard deviation values of the wind speed for each range considering that the data measured at $h = 60$ m represent the reference values.

To calculate the turbulence intensity values for the specified domains of average speed, respectively the determination for each range of the average speeds (1-20 m/s) of turbulence intensity values, was used a 4th degree polynomial interpolation curve for the best approximates the distributions of turbulence values on the considered domain. (Fig. 1.4).

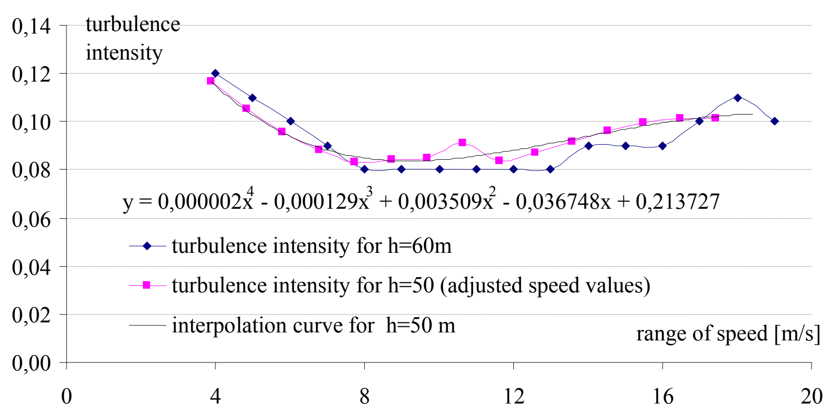

Fig. 1.4 Polynomial interpolation curve for turbulence intensity 60-50 m

Using a 4th degree curve interpolation, the relative errors resulting by comparing the calculated turbulence intensity values and measured values at $h = 50$ m are acceptable (below 10%).

The 4th degree interpolation curve, given by the expression:

$$y = 0.000002 \cdot x^4 - 0.000129 \cdot x^3 + 0.003509 \cdot x^2 - 0.036748 \cdot x + 0.213727 \quad (9)$$

practically achieve a redistribution of turbulence intensity values in the specified domains.

Based on the algorithm described above, were determined the average speed at the height of 20 m and turbulence intensity distributed to speed domains.

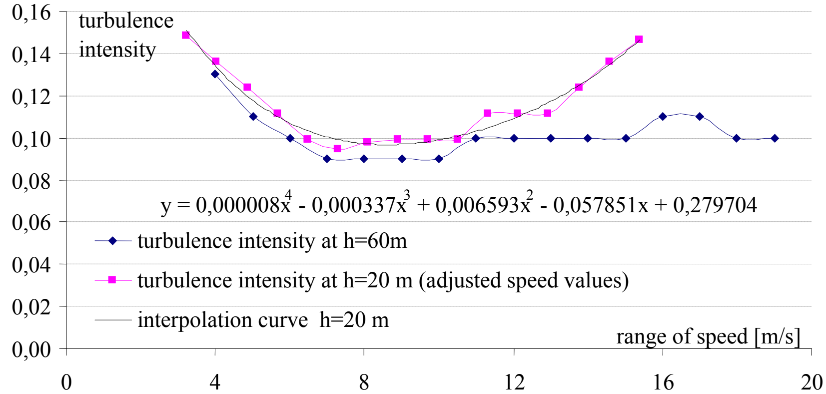

Fig. 1.5 Polynomial interpolation curve for turbulence intensity at 60-20 m

Analyzing the results the turbulence level for small heights becomes an important one in terms of accentuation of friction between air layers effect of the roughness of the ground. The algorithm established a turbulence intensity for the 20 m height, which for the value of speed of 15 m/s represents 14%.

Table 7

Extrapolation of the turbulence level from 60 m to 20 m

Range	Wind speed range	Standard deviation	Adjusted speed values for h=20m	Turbulence Intensity at h= 20 m	4^{th} degree polynomial interpolation
		measured	calculated	measured	calculated
	[m/s]	[m/s]	[m/s]	[-]	[-]
	0.... 0,49	-	-	-	-
1	0,5.....1,49	-	-	-	-
2	1,5.....2,49	-	-	-	-
3	2,5.....3,49	-	-	-	-
4	3,5.....4,49	0,48	3,24	0,15	0,13
5	4,5.....5,49	0,55	4,05	0,14	0,12
6	5,5.....6,49	0,60	4,85	0,12	0,11
7	6,5.....7,49	0,63	5,66	0,11	0,10
8	7,5.....8,49	0,64	6,47	0,10	0,10
9	8,5.....9,49	0,69	7,28	0,09	0,10
10	9,5...10,49	0,79	8,09	0,10	0,10
11	10,5....11,49	0,88	8,90	0,10	0,11
12	11,5...12,49	0,96	9,71	0,10	0,12
13	12,5...13,49	1,04	10,52	0,10	0,13
14	13,5...14,49	1,26	11,33	0,11	0,14
15	14,5...15,49	1,35	12,14	0,11	0,14
16	15,5...16,49	1,44	12,95	0,11	0,15
17	16,5...17,49	1,70	13,75	0,12	-

18	17,5...18,49	1,98	14,56	0,14	-
19	18,5...19,49	1,90	12,95	0,15	-
20	19,5...20,49	-	-	-	-

5. Conclusion

Wind conditions in terms of average wind speed and concerning dynamic effects related to turbulence, establish the operating conditions for the wind systems which are strongly influenced by the randomness of wind energy.

Flow modeling correlated with field measurements offers the possibility of establishing technical solutions for the wind turbines which on the one hand to ensure a level of efficiency close to the estimations and last but not least, be adapted to specific operating regimes.

The efficiency of wind systems and especial small wind systems are strongly influenced by the preliminary wind assessment and the turbulence regime in the location because the hub height is not large and the influence of the orografy is important. Accurate and reliable measurements and estimation for the two parameters regarding local wind condition, mean wind speed and turbulence regime ensure a suitable solution for equipment or design requirements.

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