A simple method to estimate the effect of climatic conditions on power curves.

Vinay Belathur Krishna, Michael Pram Nielsen, Alvaro Matesanz Gil and Henrik Kanstrup Jørgensen
Vestas Wind Systems A/S, Hedeager 42, 8200 Aarhus N, Denmark

Rafael De Vecchi, Marcello Trombelli Junior
Vestas do Brasil Energia Eólica Ltda
Avenida Chedid Jafet, 222, Torre D – 4º Andar São Paulo, Brazil

radvc@vestas.com, algil@vestas.com

Abstract: The scientific community agrees in accepting that climatic conditions affect the power curve of a wind turbine. It does not mean that turbine performance is reduced, turbine output is a function of input wind and, in general, they are producing what is expected for that specific wind conditions.

The effort of that community to understand the physical phenomena related to the effect of such variables have originated the definition of normalization procedures in the main standard used to measure the performance of wind turbines. The Edition 2 of IEC61400-12-1 issued on March 2017 includes some procedures to account for turbulence, shear exponent, inflow, wind veer, etc.

The knowledge of the effect of climatic conditions of a specific site on power curves is of paramount importance to determine the possible energy output of a wind farm. The current methods are based on the use of experimental data obtained in multiple sites that sometimes provide a good approximation for the average value of an infinite number of wind farms but fails to evaluate the results for a specific wind farm. Due to the lack of available data the variables can not be analyzed in detail as it is necessary to have a minimum of points to consider the results statistically significant.

The authors propose an approximate method that determines the effect of climatic conditions on power curves. This method is very robust and extremely fast which allow its use also in combination with temporal series what increases even more the precision of the evaluation of production in the wind farm.

The paper describes the effect of different climatic variables on power curve and the procedures developed to simulate the effect of different variables such as turbulence, shear exponent, etc. The second part of the paper presents part of the validation campaign for that tool. It consists in comparisons between the power curves obtained by the approximate method and the ones computed by VTS, the aeroelastic code use in Vestas to compute power curves. Finally, the procedure described in this paper is applied to evaluate the effect on production of boundary layer shapes that do not follow an exponential low. This feature is especially important for evaluating the expected production in sites with katabatic and anabatic winds.

Keywords: Power Curves, turbine performance, uncertainty.

Introduction:

The estimation of energy output is of paramount importance in the evaluation of viability of a wind energy project. The accuracy of this process is critical as any overestimation of production would originate financial losses during the operation of the wind farm and an underestimation could make impossible to identify projects with good economical perspectives. This is especially important in auctions where an artificial reduction of production could lead to excessive high cost of energy. In that situations the wind farm developer could lost the opportunity of a very good deal just because the inaccuracy of production estimates.

To have and accurate estimation of the energy production is necessary to determine the wind characteristics in the site. This analysis should include some long-term correction [1-2] to estimate with more precision the average wind speed expected during the lifetime of the project.

The evaluation of the wind speed, and hourly distribution, in only the first step in the process as the response of the wind turbines depends on the characteristics of the wind [3-8], and therefore, that influence shall be determined from the very beginning to allow an accurate evaluation of possible energy output. Most of the discrepancies observed in the analysis of performance of wind turbines can be explained by the characteristics of the wind during the test.

The power curve of the turbine depends, among others, on turbulence levels, shape of boundary layer and wind veer. These wind characteristics could change with wind direction, season, hour of the day, etc. The analysis of these wind characteristics and their variation is essential to determine with enough precision the output of a wind farm. To provide a better representation of flow characteristics many advances in CFD have been applied to determine the flow in wind farms [9-11] and to determine the energy output with improved accuracy [12-13].

Once the conditions of the wind have been properly stablished for a wind farm it is necessary to have a method that provides the output of the turbine. When the variability of climatic condition is reduced the simple method of using the power curve provided by the supplier of the wind turbine could give enough accuracy. This accuracy could be improved if a Climatic Specific Power Curve is applied.

When the variability of climatic condition exceeds some limits (or the order of an interval of 6% in turbulence and 0.3 in shear exponent) the behavior of turbine is non-lineal and the above approximation does not provide the required accuracy. This also happen when the wind characteristics have a bimodal behavior and values are not distributed around average values. Figure 1 shows an example of bimodal behavior in a wind farm. In that site there is two seasons one with a wind characterized by high turbulence and another with low turbulence. The average values of intensity of turbulence have very little probability of occurrence in that site.

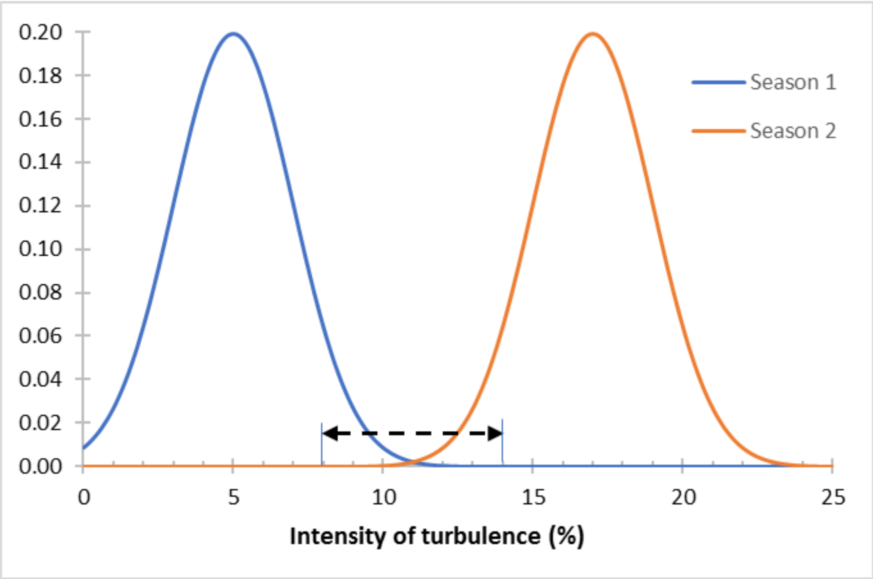

Figure 1. Frequency distribution for two seasons with different turbulence

The methodology defined by IEC61400-12-1 [14-15] could give some inspiration to the correction of power curves by climatic conditions but has been developed to measure the performance of the turbines not to evaluate with more accuracy the production of a wind farm.

Other authors propose the use of an empirical method to correct the power output of turbines with climatic conditions. The method is based on the determination of a series of matrices with the correction for climatic variables obtained by the analysis of previous measurements [16]. This method could reduce the differences observed in the analysis of post-construction energy output [17-18] but as it is based in average values its application for a specific wind farm and a specific wind turbine would be less accurate than a method developed for this particular turbine.

Another disadvantage of that empirical method is that correction matrices will follow the average behavior of the sample of turbines analyzed. A very specific problem such as stratification or change on shape of boundary layer would be very difficult to analyze with that methodology.

The method proposed by the authors is based on simple physical consideration and is so fast and robust numerically that can be applied also with temporal series what increase more the accuracy of the evaluation of production.

Analysis of non-uniformity in the flow.

The flow in the rotor plane has been considered uniform in previous editions of standard 61400-12-1[14] and therefore the wind speed is determined by the measurement only in one point. In the 2017 edition of that standard [15] the concept of rotor equivalent wind speed was introduced to incorporate in the analysis the possible effect of lack of uniformity in the flow. The equivalent wind speed is defined as the uniform velocity that has the same flux of kinetic energy through the rotor. The selection of this variable could be misinterpreted and the reader of [15] could believe that power coefficient is not affected by the flow structure. With this false assumption the power output would be just determined by the product of a constant power coefficient and the flux of kinetic energy through the rotor.

There are many physical reasons that demonstrate that power coefficient is affected by the flow structure. One of the most evident is related with the distribution of angles of attack on the blade. As the blades has not the capability of modify their twist to adequate to the change of wind speed, the distribution of angles of attack will be different from the one obtained for uniform flow. When angles of attack are different the lift and drag coefficients would change and, obviously, the power output and power coefficient would be different.

Another reason is based on the characteristics of power coefficient of turbines. This coefficient depends among other variables on pitch angle and tip speed ratio. In the region of variable rotational speed, the tip speed ratio is maintained constant and equal to the optimum one. In a simplified model of control, the turbine selects the rpm as a function of wind speed at hub height and therefore the value of speed ratio in sections of the blade placed at different heights can not be selected to adequate to its optimum value.

The effect of no uniformity of flow on power output can be analyzed by applying the BEM method. With the triangle of velocities that appear in Figure 2 the mechanical torque, dT, generated by an element of blade place at radius r can be computed by the following formula:

$$dT = \frac{1}{2}\rho\, U_T^2\, c\, (C_L \sin\phi - C_D \cos\phi)\, r\, dr$$

Where ρ is the density, U_T is the relative flow velocity, c is the chord of the blade at radius r, ϕ is the angle between relative flow velocity and rotor plane and C_L and C_D are the lift and drag coefficient respectively.

The value of relative flow velocity is:

$$U_T = \sqrt{\left((1-a)\,U_0\right)^2 + \left((1+a')\,\Omega\, r\right)^2}$$

Where U_0 is the wind speed, Ω is the rotational speed and a and a' are respectively the axial and rotational interference factors.

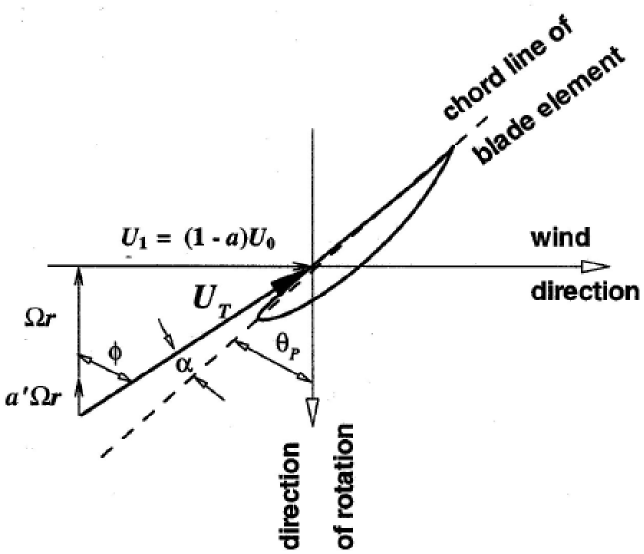

Figure 2. Velocities for blade element at radius r.

The mechanical power, dW, generated by this section of the blade is obtained multiplying torque by rotational speed:

$$dW = \frac{1}{2}\rho\, U_T^2\, c\, (C_L \sin\phi - C_D \cos\phi)\, \Omega\, r\, dr$$

And applying basic trigonometry the equation can be written as:

$$dW = \frac{1}{2}\rho\, U_T^2\, c\, \Omega\, r \left(C_L \frac{(1-a)U_0}{U_T} - C_D \frac{(1+a')\Omega\, r}{U_T}\right) dr$$

Or

$$dW = \frac{1}{2}\rho\, U_T\, c\, \Omega\, r\, (C_L(1-a)U_0 - C_D(1+a')\Omega\, r)\, dr d\theta$$

The velocity of wind in the rotor plane can be defined as:

$$U_0 = U_{HH} + u'$$

Where U_{HH} is the wind velocity at HH and u' is the change in the wind velocity with respect to the value at HH at a specific position in the rotor plane.

Without any loss of generality, the above expression can be written as:

$$U_0 = U_{HH}(1+u)$$

Then, the value of U_T can be written as:

$$U_T = U_{HH}\sqrt{\big((1-a)\,(1+u)\big)^2 + \left((1+a')\,\lambda\frac{r}{R}\right)^2}$$

Where λ is the tip speed ratio $\left(\lambda = \frac{\Omega\, R}{U_{HH}}\right)$ and R is the radius of wind turbine. For the rest of this chapter has been assumed that control of wind turbine follows the velocity of wind at hub height to determine the rotational velocity, and that these control does not react to flow non- uniformity.

This velocity can be expressed as:

$$U_T = U_{HH}(1-a)\sqrt{1 + \left(\lambda\left(\frac{1+a'}{1-a}\right)\frac{r}{R}\right)^2 + 2u + u^2}$$

Defining X as:

$$X^2 = 1 + \left(\lambda\left(\frac{1+a'}{1-a}\right)\frac{r}{R}\right)^2$$

The relative velocity can be written as:

$$U_T = U_{HH}(1-a)X\sqrt{1 + \frac{2u+u^2}{X^2}}$$

The second part in the root is the contribution of non-uniformity of flow in the rotor plane.

The term between brackets in the power equation can be written as:

$$C_L(1-a)U_0 - C_D(1+a')\Omega\, r = U_{HH}\left(C_L(1-a)(1+u) - C_D\,\lambda\left(\frac{1+a'}{1-a}\right)\frac{r}{R}\right)$$

The RHS of this equation can be written as:

$$U_{HH}\left(C_L(1-a) - C_D\,\lambda\left(\frac{1+a'}{1-a}\right)\frac{r}{R}\right) + u\,U_{HH}C_L(1-a)$$

Defining Y as:

$$Y = C_L(1-a) - C_D\,\lambda\left(\frac{1+a'}{1-a}\right)\frac{r}{R}$$

The equation for mechanical power can be written as:

$$dW = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)X\sqrt{1\, + \frac{2u+u^2}{X^2}}\ \left(Y + u\, C_L(1-a)\right) c\ \frac{r}{R}\, dr d\theta$$

It is clear that power output depends on third power of velocity of hub height but it is not possible to infer from this formula that variation of power due to the existence of non-uniformity depends on variation of flux of kinetic energy. When the change of velocity in the rotor plane is much smaller than the velocity at hub height, $(u \ll 1)$, the formula can be approximated by:

$$dW = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)X\left(1\, + \frac{u + 0.5\, u^2}{X^2}\right)\ \left(Y + u\, C_L(1-a)\right) c\ \frac{r}{R}\, dr$$

That can be written as:

$$dW = dW_o + dW_1\, u + dW_2\, u^2 + dW_3\, u^3$$

With

$$dW_0 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)X\, Y\, c\ \frac{r}{R}\, dr$$

$$dW_1 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)\left(\frac{Y}{X} + X\ C_L(1-a)\right)\ c\ \frac{r}{R}\, dr$$

$$dW_2 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)\frac{Y}{X}\left(\frac{1}{2} +\ C_L(1-a)\right)\ c\ \frac{r}{R}\, dr$$

$$dW_3 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)\frac{1}{2X}\ C_L(1-a)\ \ c\ \frac{r}{R}\, dr$$

The above expressions can be further simplified for profiles of high aerodynamic efficiency neglecting the terms proportional to drag coefficient. As $u \ll 1$ the contribution of second and third order terms can be neglected. With these simplifications the power produced is:

$$dW_0 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)^2 X\ \ C_L\, c\ \frac{r}{R}\, dr$$

$$dW_1 = \frac{1}{2}\rho\, {U_{HH}}^3\, \lambda\, (1-a)^2 X\, C_L\left(1 + \frac{1}{X^2}\right)\ c\ \frac{r}{R}\, dr$$

And

$$dW = dW_o\left(1 + u\left(1 + \frac{1}{X^2}\right)\right)$$

When a turbine is running in the region of variable rotational speed the value of axial induction factor is close to the optimum one, 0.3, and the value of rotational induction factor can be considered negligible. As λ is of the order of 10 the value of X^2 is, for most part of the blade, greater than 10.

$$X^2 \approx 1 + \left(14.3 \frac{r}{R}\right)^2$$

Therefore $X^2 > 10$ for $\frac{r}{R} > 0.21$ and $X^2 > 5$ for $\frac{r}{R} > 0.14$

According to this the mechanical power of the turbine in the region of variable rotational speed and in the region where rpm is set to the minimum one can be approximated by:

$$dW = dW_o(1 + u)$$

Therefore, for the streamtube of radius r the change of mechanical power extracted from the wind in this part of the rotor would be proportional to the change of volumetric flow rate. Ratio between the power for the real flow and the one for uniform flow is:

$$\frac{dW}{dW_o} = (1 + u)$$

The RHS of this equation is the ratio of volumetric flow rates. If this operation is repeated for all streamtubes in the rotor the conclusion is that in a first approximation the change of power output of the turbine should be proportional to the change of flow rate. If the power output is proportional to the flow rate the average velocity that approximate the behavior of turbine should be the simple average of velocity and not the one that provide the same flux of kinetic energy.

This result is similar to the one obtained for other rotational machines such as fans where the power can be estimated as the product of volumetric flow rate by the increase of pressure (or decrease in case of turbine). For small variations of flow rate the change of pressure is governed by the rotational speed. If this speed is maintained constant the ratio between powers is just the ratio between volumetric flow rates.

Simulation of the effect of turbulence

The effect of turbulence can be simulated by applying the classical method of combining the zero turbulence power curve with a distribution of velocity around the average value that simulates the effect of turbulence. This method is described in the IEC61400-12-1 Ed. 2. The main difference is that in the Standard the power curve for zero turbulence is derived from the measurements and in the method used here that power curve has been obtained by using VTS the program used by Vestas to simulate the turbine output.

Once the power curve for zero turbulence is known the value of power output for any value of turbulence is obtained assuming that turbine follows that curve instantaneously. The variation of velocity is simulated with a normal distribution with an average velocity equal to the velocity of the ten-minutes period and with a standard deviation equal to the turbulence multiplied by the average velocity. The power output for velocity *v* is obtained by the following expression:

$$W(v, IT) = \int_{-\infty}^{\infty} W(t, 0)\ f_P(t)\ dt$$

Where $W(v, IT)$ is the value of power curve for velocity v and intensity of turbulence, *IT*, $W(v, 0)$ is the value of power curve for velocity *v* and zero turbulence and f_P is the frequency density function of velocity, that is represented by a *N(v,IT v).*

The Figure 3 shows the comparison between the approximate power curve obtained with the above described formulation and the one obtained by using VTS for an intensity of turbulence of 0.15. In that figure is possible to see that VTS results and approximate ones have an extraordinary good agreement for low velocities and that VTS power curves are more energetic close to rated velocity.

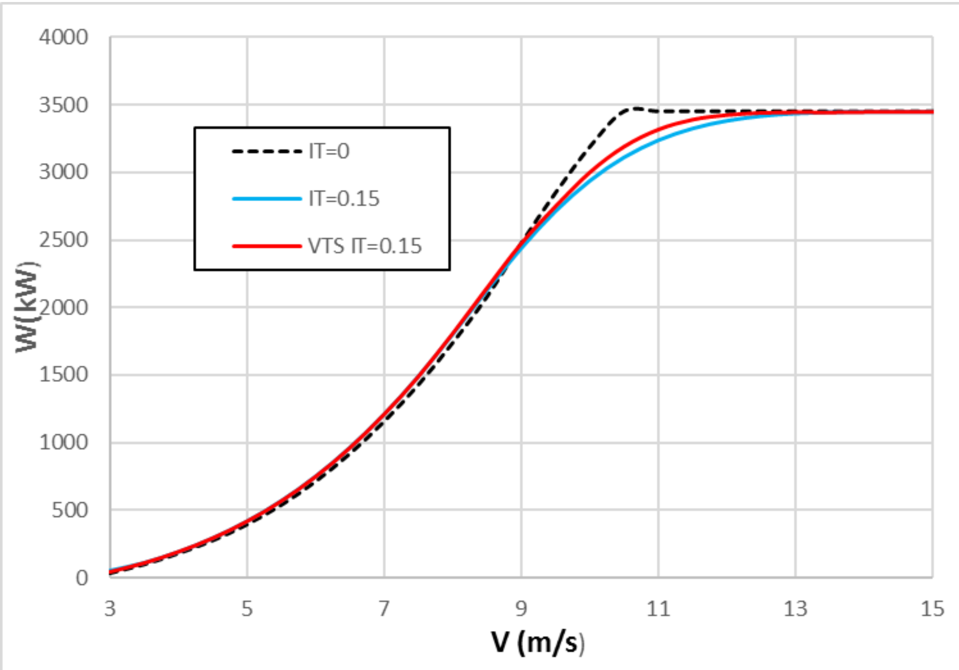

Figure 3. VTS and approximate power curve for IT=0.15

The increase of production in the region close to rated velocity is explained by the application in the control of the turbine of features such as power boost that improves the output of the turbine in that region and that can not be simulated by this simplified methodology. Table 1 gives and overview of differences in percentage of production between VTS, AEP_{VTS}, and approximated power curves, AEP_{apr}, for different IT and average wind speeds. The AEP deviation is:

$$AEP\ Deviation\ (\%) = 100\frac{AEP_{VTS} - AEP_{apr}}{AEP_{VTS}}$$

The good approximation obtained by this simple method is explained by the different characteristics times that appear in the problem. The characteristic time for atmospheric turbulence is ten minutes, therefore any change of velocity that happen in a smaller time is considered as ambient turbulence. The detailed analysis of the effect of turbulence on turbine shows that these times are extremely high compared with the characteristics ones in the aerodynamics of turbine. For example, the characteristic time for a profile is of the order of the residence time for this profile, for a chord size of 1 m. and a profile velocity of 50 m/s the residence time is 0.02 seconds. It means that for profile any change with a period higher than 0.2 seconds is not seen as turbulence, it is just a change in boundary conditions. The content of ambient turbulence with period higher than 0.2 seconds can be simulated without problem with the simplified method.

IT	**7.5**	**8.5**	**9.5**
0.00	0.00	0.00	0.00
0.10	-0.84	-0.78	-0.70
0.15	-0.88	-0.82	-0.75
0.20	-0.59	-0.55	-0.50

Table 1. AEP deviations(%) for different V and k=2.

Another important aspect is the size of the eddies associated to turbulence. The characteristic size of an eddy can be obtained by the Strouhal number, a nondimensional value that relates frequency, size and velocity of different phenomena. The Strouhal number has a value in the range of 0.1 to 0.2 for most flows of interest. This number is defined as:

$$St = \frac{f\,L}{U}$$

where f is the frequency of vortex, L is the characteristic length and U is the flow velocity.

Assuming a value for Strouhal number of 0.1 and a value of wind velocity of 10 m/s the frequency for having a length of 10 meters is 0.1, therefore turbulence with frequency higher than 0.1 Hz has a size smaller than 10 m. The effect of randomly distributed vortex of small size compared with the rotor size can be considered neutral, as the effect of one vortex would be cancelled by another one.

Simulation of the effect of non-uniformity of flow

In this chapter the effect of non-uniformity of the flow that are not originated by turbulence are being analyzed. The characteristic time of these phenomena is the passing time of the blade that is much smaller than the characteristic time for changing the average wind speed in the rotor originated by turbulence. This different time scales makes that these phenomena could be considered as uncoupled with turbulence.

As demonstrated previously the analytical relative variation of power output is proportional to the relative variation of volumetric flow rate. In this chapter that result will be compared with the results of numerical simulation performed with VTS.

The method to define the variation of the power curve for a specific distribution of wind speed in the rotor is very simple. For the rest of this document it is assumed that a power curve with specific climatic conditions for the turbine is available. The effective velocity is defined as:

$$v_{eff} = \frac{1}{V_{HH}} \sqrt[n]{\frac{\int V^n dA}{A}}$$

V_{HH} is the velocity of wind at HH, A is the rotor area, dA is the differential of area and V is the velocity in this differential of area, n is a constant that allows to investigate of different weighting factors.

The first step is to define the effective velocity for the climatic conditions that have been used to define the power curve. Once this value has been determined the power curve provides a relationship between effective velocity and power output. For a different effective velocity the power output is obtained by interpolating in the function defined previously. In case that effective velocity for the provided power curve is 1 the interpolation would be done directly in the power curve. This is not the case for Vestas turbines as the power curve is provided for a shear exponent of 0.15 to include such physical effect on the supplied power curve [15].

For the rest of the document it has been assumed that velocity in the rotor is only a function of z. With that assumption the effective velocity can be computed as:

$$v_{eff} = \frac{1}{V_{HH}} \sqrt[n]{2\,\frac{\int_{HH-R}^{HH+R} V(z)^n \sqrt{R^2 - (z-HH)^2}\; dz}{A}}$$

If a change of variables to nondimensionalize z and HH is applied the above equation is transformed to:

$$v_{eff} = \sqrt[n]{\frac{2}{\pi} \int_{h-1}^{h+1} v(t)^n \sqrt{1-(t-h)^2}\; dt}$$

Where:

$$t = \frac{z}{R} \qquad h = \frac{HH}{R} \qquad v_{(t)} = \frac{V(z)}{V_{HH}}$$

It could be reduced to

$$v_{eff} = \sqrt[n]{\frac{2}{\pi}\int_{-1}^{1} v(\xi)^n \sqrt{1-\xi^2}\ d\xi}$$

With $\xi = t - h$

Shear exponent effect

In this case the non-dimensional velocity in the rotor plane is:

$$v(\xi) = \left(\frac{\xi + h}{h}\right)^{\alpha}$$

Substituting this formula in the effective velocity equation for a value of n=1 the following integral is obtained:

$$v_{eff} = \frac{2}{\pi}\int_{-1}^{1}\left(\frac{\xi + h}{h}\right)^{\alpha} \sqrt{1-\xi^2}\, d\xi$$

Unfortunately, this integral can only be solved by numerical calculation. This integral is presented in Figure 4 for different values of parameter h.

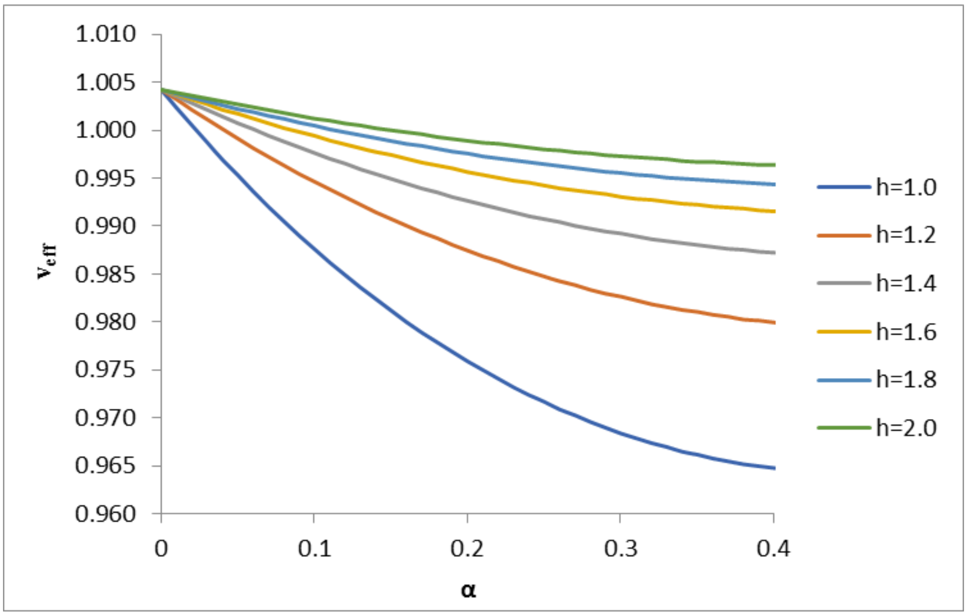

Figure 4. Effect of shear exponent on v_{eff} for different values of h for $n=1$

In Figure 5, the results obtained for different values of exponent n have been compared with the results obtained with VTS. The calculation of energy production has been done for an average velocity of 7.5 m/s and for k=2. The value that appear in Figure 5 is the change in AEP relative to the one obtained for the power curve of α=0.15 that is the shear exponent used by Vestas to provide power curves [19].

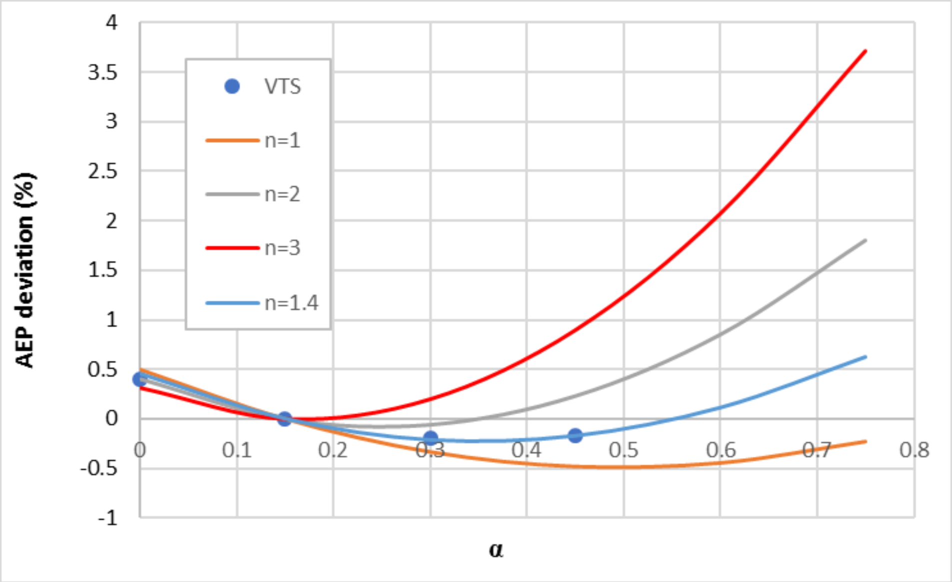

Figure 5. AEP deviation between VTS and effective velocity approach

The value of exponent n=1.4 is the one that provides a better fit between the approximate method and the numerical situation. The use of an exponent of n=1 slightly overestimate the effect of non-uniformity of the flow and the value of n=3 clearly underestimate the effect of shear exponent providing production about 1% higher than the obtained by numerical simulation for shear exponents of 0.45

Conclusions

In most of the cases the pre-construction energy estimate is performed with a unique power curve that can not take into account the variation of climatic conditions that happen in the site. This is one of the reasons that explains the extremely big variability observed in the post-construction evaluations of energy, where average value of production for a big number of wind farms is predicted with reasonable accuracy but the precision for individual project is more than questionable.

In some analysis these discrepancies are associated to the turbines when in reality are originated by a lack of knowledge of wind conditions. In any case, without a proper characterization of the wind is not possible to determine the origin of deviations in energy estimates.

The accuracy of this pre-construction energy estimate could be greatly improved if the climatic conditions of the site are used to determine the output of the turbines for the specific conditions.

The results could be further improved if the energy estimation is done by using temporal series and not prescribed wind distribution.

To perform the analysis with time series is necessary to have a fast and robust method to determine the output of the turbine for the climatic condition of the ten-minute period under study.

The authors propose to use the classical way of combining the zero turbulence power curve with a normal distribution of velocity to simulate the effect of turbulence. The zero turbulence power curve should be defined by the supplier of the turbine to remove the inaccuracies associated to the method proposed in the IEC61400-12-1. With this approximation the energy is slightly underestimated as turbines could include control features to improve production near rated velocity.

To simulate the effect of climatic variables such shear exponent, wind veer and different shapes of boundary layer the authors propose the use of the effective velocity of the rotor. This velocity would be used with the power curve provided by the supplied to obtain the response of the turbine to these variables.

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