Uncertainties in the estimate of wind energy production

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ABSTRACT

The Annual Energy Production (AEP) estimated over the lifecycle of the project is one of the most important factors to determine the profitability of wind power project. The methods used to estimate the AEP in a wind farm requires an assessment of the uncertainties associated at all steps. To finance a wind power project, banks requires that the developer submit the uncertainties related to the estimation of AEP's wind farm, to mitigate errors and increase the project reliability. The appropriate assessment of uncertainties is critical to determine the feasibility and risk in developing a wind energy project. This study presents the main sources of uncertainty in the energy estimate process in wind farms. This information is important for the correct analysis of the economic viability of the project.

KEYWORDS: Wind Power, Uncertainty, Annual Energy Production

1 INTRODUCTION

The energy production in a wind farm follows a stochastic principle and, as such, requires a statistical analysis in which production estimates should be associated with occurrences probabilities.

An uncertainty analysis is often performed as part of a wind farm energy yield assessment. The economic viability of a wind farm requires an analysis of the risks associated with the production uncertainties.

The Section 3 this paper describes the main sources of the uncertainties in an energy assessment. Each wind farm development uncertainties must be individually determined and then calculated for the entire project. The are several methods, such as the IEC method (IEC 61400-12 Power Performance Testing) for the evaluation of measurement uncertainty or the Monte Carlo method, which lead to different results related to the different processes.

An interesting way to present the project uncertainties is by giving the probabilities of exceedance in terms of expected annual production of the wind farm.

In the financing process of wind farms, banks have specific requirements in order to ensure that the energy estimate has the smallest error margin possible. In Brazil, due to of auctions, the Energy Research Company - EPE, demands a declaration issued by an independent certifying, declaring the Physical Guarantee (GF), which is the annual energy availability for each wind farm competing in the energy auction.

In order to mitigate the risk that energy production be less than the one on contract, the Physical Guarantee of the wind power generated must be calculated taking into account all sources of uncertainties in the project, so that the certified energy can bear a 90% probability, being attained or exceeded. This value is called P90.

According to Tolmasquim et.al. (2013) the economic viability of wind energy production within the regulatory framework of the Brazilian electricity market emerged for the need for a set of specific rules, aimed at the following objectives:

- To imbue the business agent with the effective production of the energy contracted;
- To minimize cost of energy, reducing the financial cost of projects, mitigating uncertainty in revenues from energy sales;
- Encourage the efficient procurement of the wind farm; and
- Reduce the risk of non-compliance of the contracted energy amount.

With the current energy auctions rules, entrepreneurs are penalized for producing below the contracted amount of energy, pursuant to a tolerance margin.

Reducing uncertainty by increasing the quality of the criteria design is the only way to keep the financial risk of a wind farm within acceptable limits for financiers, besides providing greater security in meeting energy demand.

It is important to understand the main sources of uncertainties in a wind farm project in order to reduce their magnitude and then accurately calculate its impact on yield forecasts.

2 LITERATURE REVIEW

There are many references to research about uncertainties in the estimation of the wind farm energy production.

To name a few, in Lira (2012) is presents the main sources of the uncertainty in wind energy production, in Pedersen et.al. (2006) is presents an analysis of the performance of some types of anemometric, in Mortensen et.al. (2006), Corbett (2012) and Mortensen et.al. (1997) are presents the uncertainty about the wind flow simulation models and in Lackner, M. A. (2008) is present new approach for wind energy site assessment considering uncertainty.

3 OBJECTIVE

The calculation of the estimative energy production from a wind farm is subject to uncertainties that must be accounted for in order to assess the risk of investments based on the accuracy of the estimated energy production.

The main goal of this paper is to present the main sources of uncertainty in energy production estimate process for wind farms in order to identify the expected improvement in energy reliability and reduce the financial risks of the projects.

3 MAIN SOURCES OF UNCERTAINTIES

The main sources of uncertainties can be split into two groups: Wind Resource Uncertainty and Energy Production Uncertainty.

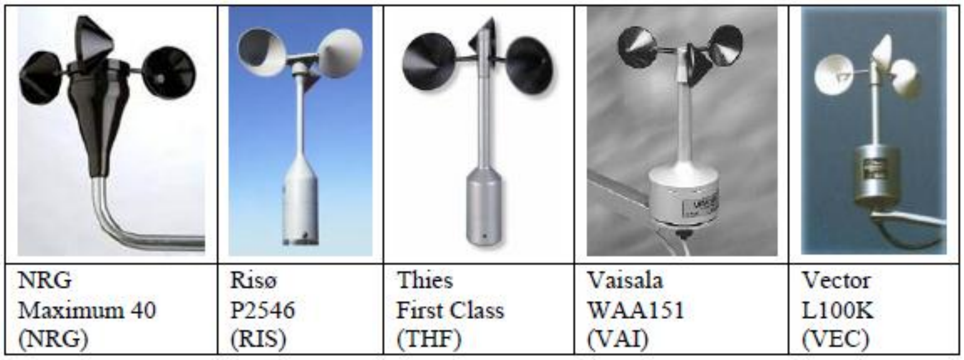
3.1 - Wind Resource Uncertainty

This uncertainty has to do with limitations in the measurement process at meteorological tower. Included the uncertainties associated with the type of the sensor, installation and calibration of sensors, location of the towers, etc.

To turn the uncertainty of the wind resource into uncertainty in energy production the sensitivity factor is required. The sensitivity factor corresponds to the variation in energy production caused by wind variation, it is specific value for each project. Energy production and wind speed shows no linear relationship.

3.1.1 - Sensor accuracy

The quality of results is directly dependent on the quality of equipment and the way they are installed at the meteorological tower. The costs of a high-quality measuring system and its appropriate installation are small when compared with the costs of a wind farm. It is recommended the use of the anemometers models *This First Class* or *Vector*, which despite their higher prices, they have reduced measurement uncertainties when other sensors on the market are taken into account. The Fig. 1 shows the main models of the cup anemometers.



NRG Maximum 40 (NRG)	Risø P2546 (RIS)	Thies First Class (THF)	Vaisala WAA151 (VAI)	Vector L100K (VEC)

Fig. 1- Main models of the cup anemometers. *Source*: Pedersen et.al. (2006)

According to IEC 61400-12-1 (2005) the Eq.1 gives the operational standard uncertainty

$$u_i = (0{,}05\, m/s \ + 0{,}005 * U_i) * \frac{k}{\sqrt{3}} \qquad \text{Eq.1}$$

Where: $U_i$is wind speed bin and k is classification number

According to Pedersen et.al. (2006) the simple uncertainty range in terms of wind speed and associated with the instrument's accuracy for an isolated sensor comprises values between approximately 1% and 6%.

3.1.2 - Sensor calibration

One important aspect concerning quality warranty of wind measurement is the anemometers calibration through an appropriate wind tunnel. There are studies that show uncertainties greater than 3.5% from anemometers calibrated in various wind tunnels. For this reason, MEASNET – *Measuring Network of Wind Energy Institutes* – has issued a measurement method for measuring cup anemometers calibration, especially custom-made for wind energy.

By following this practice, institutions provide guarantee that the wind tunnels used will not differ more than 0,5% in the reference wind speeds and, thus, such a procedure will provide a small and controlled uncertainty from the anemometers certified by the aforementioned method.

Currently, the great majority of research and wind power assessment institutions require that anemometers have calibration certificates issued by institutions that have the MEASNET stamp, that is, they observe the calibration standard set by that institution.

The use of individually calibrated anemometers poses a direct impact in reducing the wind speed measurement uncertainty.

According to Coquilla et.al. (2008) the mean relative uncertainty on the calibration of various cup and propeller anemometer models is present in the Table 1.

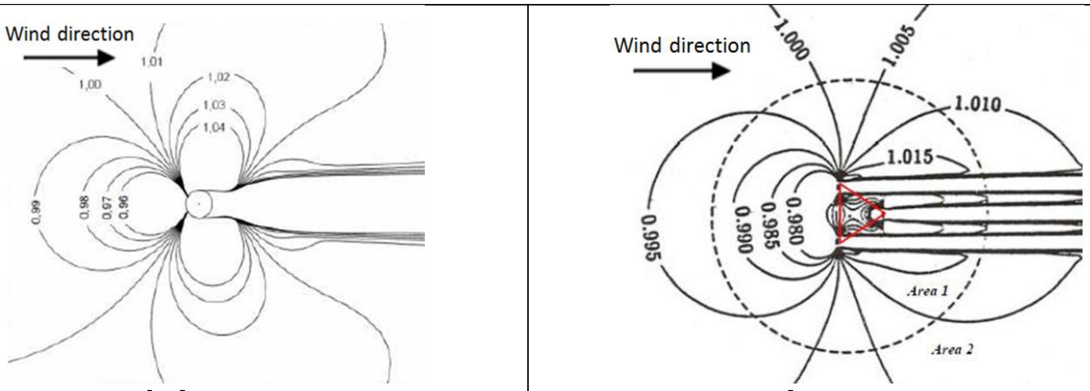
Table 1 - Mean relative uncertainty.

Cup Anemometer Model	Mean Relative Uncertainty (%)
NRG #40	1,48
NRG IF3	1,66
Risoe Cup	1,43
R.M. Young Propeller	0,50
R.M. Young Wind Monitor	0,75
R.M. Young Wind Sentry	1,02
Second Wind C3	1,64
Thies First Class	2,04
Vaisala WAA252	1,98
Vector A100LK	2,06
Vestas Cup	1,09

Source: Coquilla et.al. (2008)

3.1.3 - The uncertainty due to assembly of the sensor

The anemometers and direction sensors (wind vane) should be fixed in the tower by means of rigid booms, so there is no vibration in the sensors and thus the data measurement will suffer no interference. The length of the boom-mounted must follow pursuant to IEA's recommendations - International Energy Association. The separation between the tower and the sensors should reflect the level of uncertainty considered acceptable.
Fig. 2 shows iso-speed plot with flow disturbance because of the proximity to the tower. On the left is a tubular tower and to the right a triangular lattice tower.



Tubular Tower

Triangular Lattice Tower

Fig. 2 – Meteorological tower interference in the wind flow. *Source:* IEA (1999)

In order to minimize tower interference in the anemometer, this equipment must be apart from the met tower by a minimum distance, and positioned where the wind speed isolines interference reaches the closest value to the unit, making use of the prevailing direction of wind as reference.
The IEA´s standard guidelines recommends for tubular towers and a 0,5% error, the minimum distance between the sensors and the tower be 8,5 times the diameter of the tower, measured from the center of the tower. For lattice towers and a 0,5% error, the distance should be at least 5,7 times the width of the face. It is recommended, however, that the boom-mounted should not be much bigger than this measure to reduce vibrations.

3.1.4 - Uncertainty in the long-term wind prediction

The wind displays a stochastic behavior where a significant interannual variability is observed, that is, wind speed average may vary from year to year.
Wind measurements in short periods (1-3 years) are not indicative of long-term wind resource due to interannual variability.
Therefore, to assesses correctly a local wind potential a long period of data is required to reduce the error associated with these wind behavior changes over the years. Thus, to reduce errors in the estimate of the wind farm energy production, a data correction measured on site with long-term data is carried out. This correction improves the estimate of long-term wind speed, but also brings uncertainty in the process.
To analyze the uncertainty in the long-term wind prediction is important take into account the uncertainty on historical wind conditions and the uncertainty in future wind variability.
The uncertainty in the historical wind conditions is related with the correlation between the target site (measured data) and the reference station (long-term data). The weaker the correlation with

the reference station, the larger the uncertainty in the adjusted long-term wind resource at the target site, some estimates are given in the Table 2.

Table 2 - Wind Speed correlation uncertainty as a function of R^2

Correlation coefficient (R^2)	Wind Speed correlation uncertainty
> 0.9	< 1 %
0.9 - 0.8	1 - 2%
0.7 - 0.6	3 - 5%

Source: *GL Garrad Hassan (2011)*

The uncertainty in future wind variability, in consideration of conducted studies NYSERDA (2010), should be approximately 1,4% (10 years) and 2,2% (25 years).

3.1.5 - Uncertainty in the wind flow simulation

The wind flow model is not always able to describe the wind behavior of the meteorological towers to the location of turbines. The terrain complexity, local roughness, the existence of obstacles and the distance of each turbine from the meteorological towers are among the factors that determine the magnitude of uncertainties. The range of uncertainty can be very wide, but a typical range is 3% - 6%.

3.1.6 – Other

Other sources of uncertainties in wind resource must be taken into consideration: Uncertainty in vertical wind extrapolation, uncertainty in the numerical simulation of wakes, uncertainty of wind data availability, etc.

3.2 - Energy Assessment Uncertainty

3.2.1 - Uncertainty due to Power curve

The power curve of a wind turbine is the curve that indicates the power output for each specific wind speed, and thus is one of the main parameters for estimating energy production. Due to terrain characteristics, the wind flow often displays different features from those in which the characteristic curve of the wind turbines had been designed. This may reflect different power curve output. Variables such as turbulence and topography can play a significant role in the variation of the power curve wind turbine.

When the power curve measurement test is carried out according to the international procedures, the uncertainty typical is between 4 and 6%. If the power curve measurement test is not made, the uncertainty of the power curve can be seen between 8% and 10%.

3.1.6 - Other

Uncertainty due to Electrical losses, Uncertainty due to Energy availability, etc.

4 UNCERTAINTY CALCULATION METHODS

There are two methods for calculating uncertainties: the deterministic method and the Monte Carlo analysis.

According to Fontaine et.al. (2007) the deterministic method is based around the assumptions that the different uncertainties are independent and that there is a linear relationship between the input uncertainties and the output uncertainty. The various individual uncertainties are summed using the Root Means Squared (RMS). This method does allow for the magnitude of the individual uncertainties to be determined.

The Monte Carlo method for estimating energy uncertainties is a stochastic method simulating the behavior of a physical system a large number of times. In a wind farm uncertainty analysis, these simulations produce wind farm outputs while randomly varying the uncertainties according to a defined probability distribution. The final uncertainty estimates are then determined from the distribution of the simulated outputs. This allows for non-linear relationships between the different uncertainties since the final uncertainty is not the result of summing the various uncertainties.

5 ENERGY AND PROBABILITY OF EXCEEDANCE

The methodology used to obtain the total uncertainty of the project, the various sources of uncertainty combined, may vary from company to company. Therefore, the same project, when carried out by more than one company, may produce different overall uncertainty regardless the use of the same data.

To properly estimate energy production, in addition to evaluate the project's uncertainties, it is essential to consider all energy losses as the electrical loss, unavailability of wind turbine, unavailability of electrical grid, wake loss, to name a few.

Following calculation of energy production and discounting all energy loss, the value of net Annual Energy Production (AEP) is attained.

The net AEP and total uncertainty determine, respectively, the mean and standard deviation for a normal Gaussian distribution. The absolute standard deviation is obtained by multiplying the total uncertainty by net AEP.

The calculated net AEP is the value of the energy production called P_{50}, central energy production estimate in the normal Gaussian distribution. This represents an energy value with a 50% probability of being exceeded.

In general, the probability of energy production distribution, assuming a normal Gaussian distribution is given by Eq.2.

$$f(E) = \frac{1}{\sigma\sqrt{2\pi}} e^{{-(E-E_m)^2}/{2\sigma^2}} \qquad \text{Eq.2}$$

Where:

$f(E)$ is the probability of production being equal to the E energy [%];

E_m is the mean of normal Gaussian distribution; The net AEP with a 50% probability to be exceeded; P_{50};

σ is the absolute standard deviation of the energy production estimate.

The Eq.2 is shown graphically in Fig. 3 indicating the P_{50} value.

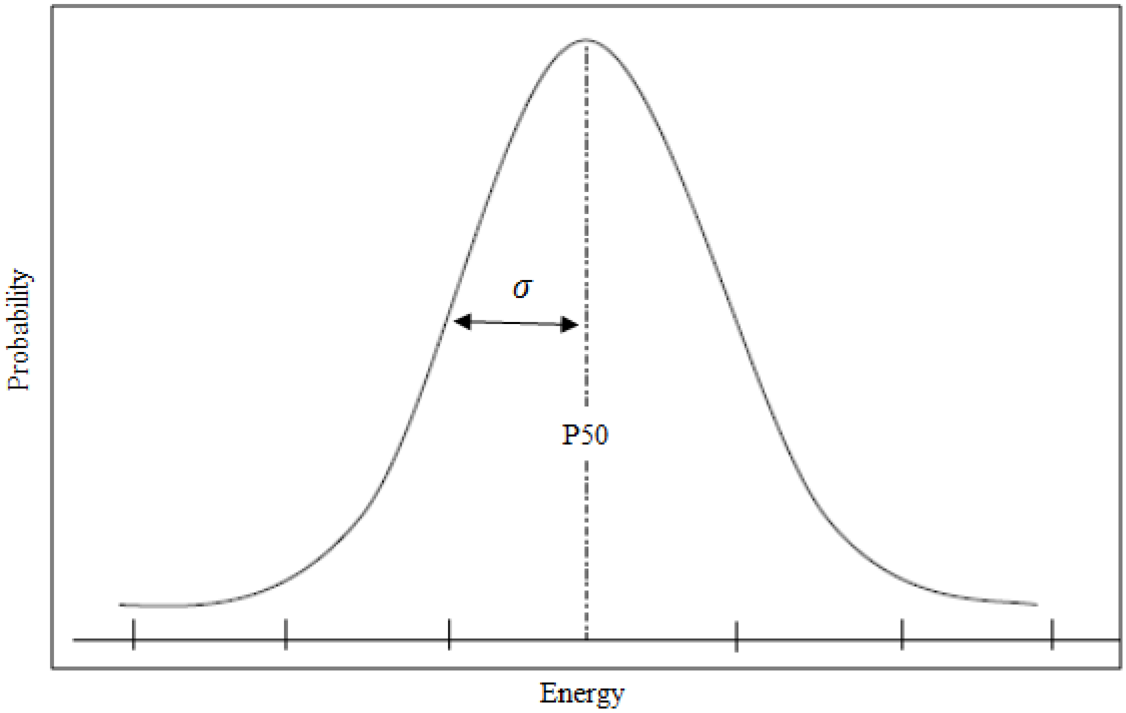


Fig. 3 - Normal Distribution – Energy production probability

To use tabulated values, they must be converted into a normalized Gaussian distribution.
To know energy production with a specific probability level, normal distribution tables for specific probabilities and the corresponding values of z need to be utilized.
With the P_{50} value, uncertainty total of the project and the z table probability, through of the Eq.3 it is possible to calculate the value in net energy production for the desired probability of exceedance.

$$P_x = P_{50} * (1 - z * Uncertainty_{Total}) \qquad \text{Eq.3}$$

Where:

P_x is the net energy production to desired probability of exceeded.
$Uncertainty_{Total}$ is the total project uncertainty.
z is the value found in the probability table.

The z value is dependent on desired probability. The Table 3 shows z values for various probability levels.

Table 3 - Normal distribution table of specific probabilities and their corresponding *z* values

Probability of exceedance (%)	z
99	2,326
95	1,645
90	1,282
85	1,036
84	1,000
80	0,842
75	0,674
50	0
25	0,674
10	1,282
1	2,326

It is important to notice that the total uncertainty is related to the energy value in P_{50}.
The net AEP in P_{90} translates a 90% probability of being attained or exceeded.
It is recommended that the total uncertainty of the project should be around 15%.
The higher the value of total uncertainty, the higher the difference between P_{50} and the other levels of probability of exceedance.

5.1 – Examples of Probability of exceedance

Following are three examples with the same amount of energy in P_{50}, but with different values for total uncertainty. The energy values in P_{75} and P_{90} (75 % and 90 % probability of exceedance) are used to show the impact caused by overall uncertainty.

5.1.1 – Example 1: P50 of 120 GWh/year and total uncertainty of 10%

The Table 4 shows a project with energy in P_{50} equal to 120 GWh/year and 10% of total uncertainty. In this example, the energy values in P_{75} and P_{90} are respectively 7% and 13% lower than the value of energy in P_{50}.

Table 4 - Example 1: P50 of 120 GWh/year and total uncertainty of 10%

P50 (GWh/year)	Uncertainty	P75 (GWh/year)	P90 (GWh/year)
120	10%	112	105
Difference from P50		**-7%**	**-13%**

The Fig. 4 shows various levels of probability of exceedance for this example.

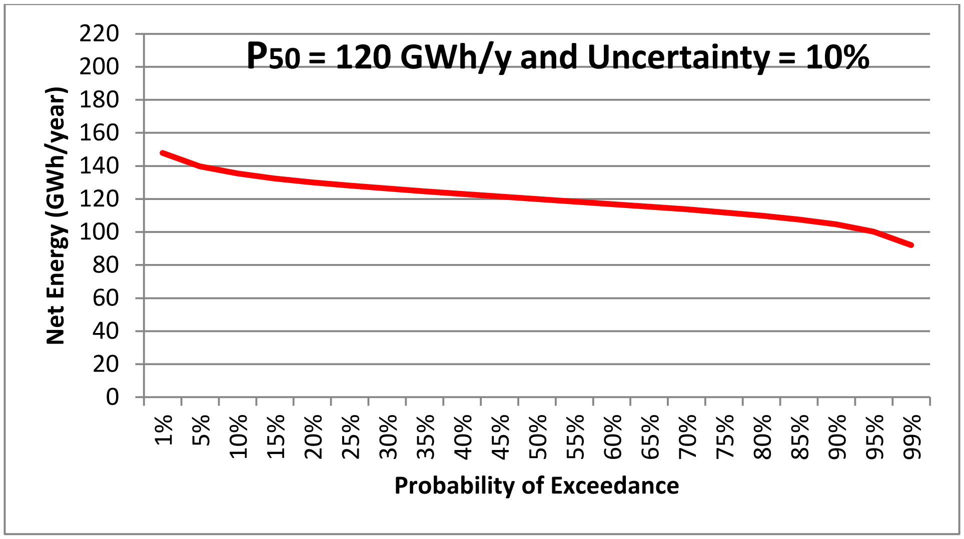


Fig. 4- Probability of exceedance: P50 of 120 GWh/year and Uncertainty of **10%**

5.1.2 – Example 2: P50 of 120 GWh/year and total uncertainty of 15%

The Table 5 shows a project with energy in P_{50} equal to 120 GWh/year and 15% of total uncertainty. In this example, the energy values in P_{75} and P_{90} are respectively 10% and 19% lower than the value of energy in P_{50}.

Table 5 - Example 2: P50 of 120 GWh/year and total uncertainty of 15%

P50 (GWh/year)	Uncertainty	P75 (GWh/year)	P90 (GWh/year)
120	15%	108	97
Difference from P50		**-10%**	**-19%**

The Fig.5 shows various levels of probability of exceedance for this example.

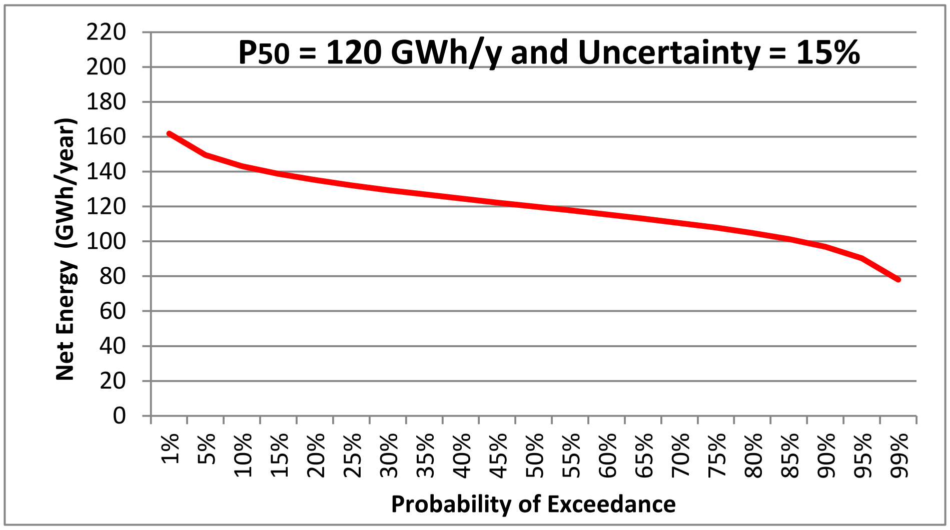


Fig. 5 - Probability of exceedance: P50 of 120 GWh/year and Uncertainty of **15%**

5.1.3 – Example 3: P50 of 120 GWh/year and total uncertainty of 30%

The Table 6 shows a project with energy in P_{50} equal to 120 GWh/year and 30% of total uncertainty. In this example, the energy values in P_{75} and P_{90} are respectively 20% and 38% lower than the value of energy in P_{50}.

Table 6 - Example 3: P50 of 120 GWh/year and total uncertainty of 30%

P50 (GWh/year)	Uncertainty	P75 (GWh/year)	P90 (GWh/year)
120	30%	96	74
Difference from P50		**-20%**	**-38%**

The Fig. 6 shows various levels of probability of exceedance for this example.

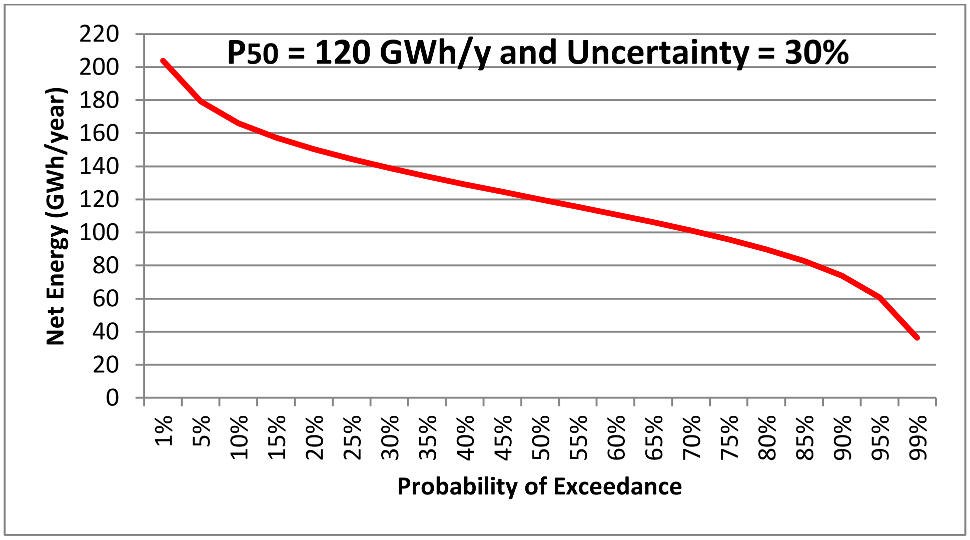


Fig. 6 - Probability of exceedance: P50 of 120 GWh/year and Uncertainty of **30%**

6 CONCLUSION

It is important to properly quantify the uncertainties of a wind project because they may represent significant variations in energy production. The uncertainty analysis is, therefore, paramount in assessing economic viability of a wind power project.

The extra costs for accurate wind monitoring are relative very small compared to a high investment in a wind energy project.

It is recommended to use first class anemometers and they need to be correctly calibrated.

Multiple measuring towers are very important to reduce the uncertainty. The maximum distance between proposed turbine location and meteorological tower should be lower than 6km for flat terrain and 2km for complex terrain.

The proper wind flow model is important to reduce the uncertainty. The linear model is recommended to flat terrain and neutral climatic conditions. For complex terrain, usually CFD model is recommended.

It is essential to define a standard methodology for the calculation of uncertainties in energy production on wind farms in order to avoid significant differences in the calculated energy from different independent certifiers.

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