Experience Feedback on 97 wind resource assessment studies in France

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Abstract

Pre-construction wind potential assessments are often associated with not negligible uncertainty levels due to the variability of the wind resource and the specific conditions of the study.

The REEPEF[1] project, carried out by Eoltech and co-financed by the ADEME[2], is a feedback experience study on 97 pre-construction wind potential assessments, aiming at comparing the estimated production to the effective production of wind parks in operation for more than one year. The sample comprises 94 operating wind farms representing 667 turbines and a total power of 1288 MW (11 separate owners and/or operators involved). The 97 pre-construction assessments were carried out by 15 independent consultancies, none of them representing more than ¼ of the studies.

To able the comparison, productions were adjusted to similar levels of availability and equivalent long term periods. Thus, the deviations between theoretical and effective productions can be explained both as the result of the uncertainty on the pre-construction assessments and the uncertainty on the actual performance of the turbines.

If the reason of the output deviation is not always easy to identify as it may result from the combination of various elements, tests were still carried out to observe if some factors seem to cause any trend. Thus, the sample analyzed was reduced to avoid as much as possible the combined effects due to separate factors. Some factors were clearly identified as increasing the overestimation of the production capacity. The uncertainty on production of pre-construction studies involving such criteria should then be refined.

[1] Full name of the study (*"Retour d'Expérience sur les Etudes de Potentiel Eolien »)*

[2] French environmental agency

1 Background and objectives

Following a call for projects by the ADEME in 2012 and with their financial support, Eoltech carried out a feedback study on energy yield assessments based on 94 projects located in France. The aim of the study is to get a feedback experience on pre-construction wind potential assessments on a significant sample in France.

The difference between an energy yield assessment based on theoretical calculations and the production capacity measured by the utility meter can be explained on the basis of 4 factors:

1- the uncertainty on the pre-construction wind potential assessment itself,
2- availability issues of the wind park,
3- the wind resource during the operating period,
4- the actual performance of the wind turbines.

The goal of this study was to compare the annual output estimated before the wind farm construction and the actual output after at least one year of operation on a significant sample of active wind farms in France. Both production estimates were adjusted on equivalent availability rates and wind resource (100% availability and 100% energy index using the decade 2004-2013 as the long term reference). Hence, the analysis of the output differentials is not affected by points 2 or 3 and focuses only on the uncertainties on the theoretical study and the actual performance of the wind park.

The study also includes an analysis of the degree of consistency between the output differentials and the factors that may influence the uncertainty on pre-construction assessments. These factors are mainly linked to the complexity of the conditions of the study (quality of the measurements, height of the measurements, complexity of the environment, etc.).

2 Sample

Eleven companies involved in the development and/or operation of the wind farms participated in this study: EDF EN, Kallista Energy, GDF Suez, Altech, IWB, Theolia France, Valorem, Eurocape, Quadran (JMB Energies), Sorgenia and Aalto Power.

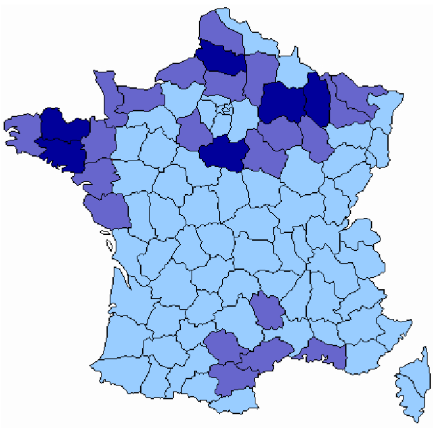
The sample consists of 94 active wind farms, including 667 turbines and representing a total power of 1288 MW (90 % of the wind farms are located in the northern half of France). The following points are noted:

- The turbines manufacturers considered are representative of the French market since the 5 most prevalent wind turbine manufacturers of this market are included and represent almost 90 % of the wind farms in the study.

- More than 15 independent consultancies are involved in the pre-construction assessments. None of them represent more than 25 % of the studies, and the three most common ones are involved in 57 % of the studies.

- More than 60 % of the wind farms consist of turbines with an average hub height between 70 and 90 m. Wind farms with turbines with a rotor diameter between 80 and 92 m are represented in the same proportion.

The map below illustrates the geographic distribution of the wind farms included in the study.



Graph 1: Wind farms location

2 Methodology

2.1 Long term reference data

Energy indexes were used in order to adjust both the production estimated from the pre-construction study and the effective production on the same long term reference period. Independently of this project, for over 4 years Eoltech has established regional energy indices for key wind farm development zones across mainland France (http://www.eoltech.fr/wind-energy-index/).

The calculation of these indices is based on reference production data (representative location of the area, standard turbine type) generated from different sources of wind data (mainly ground meteorological stations but also meso-scale data). Considered sources are independent from each other and consistent both in time and space. The use of these wind energy indices as the long term reference allows limiting the uncertainty due to the use of a single source of data, and thus is considered as more reliable (combination of several independent sources of information).

It is important to note that the object here is not the duration of the long term reference period, but that the outputs are compared are adjusted on the same reference period (ie 2004-2013).

2.2 Estimating the effective production capacity of an active wind farm

Effective production capacity refers to the net output recorded by the utility meter (EDF), adjusted to 100% availability of the turbines and adjusted to a long term reference period common to all projects. The long term period used for this study was the decade 2004-2013.

The production recorded at the utility meter is considered inherently as the most reliable information as it represents the invoiced production. It takes into account both all of the losses (wake effects, electrical losses and periods of unavailability) as well as a possible underperformance of the wind farm.

These production data were adjusted to a 100 % availability level of the wind farm. To the extent possible, in order to minimize the uncertainty of the results, technical availability rates calculated by the operator were favoured for carrying out the adjustment (ie including all causes of downtimes, whether they are attributable to the manufacturer or not). Data were filtered when availability rates were too low or not consistent regarding the effective production and the corresponding energy indexes.

The production data equivalent to 100% availability were adjusted on the long term period thanks to the energy indexes. In the scope of this study, the goal is to compare, for each operating wind farm, the differences between the production estimated from the pre-construction study and the effective capacity of production under normal operating conditions of the wind farm. Thus, if the output capacities of a wind farm appear to have changed over time (possible evolution of the wind park performance), the project focuses on the period corresponding to the highest output capacities (based on the assumption that a wind farm can "under-perform" but typically does not "over-perform").

2.3 Estimating "theoretical output" from the review of pre-construction study

All of the 97 pre-construction reports were reviewed in order to collect the theoretical output comparable to the effective output estimated (ie corresponding to 100% availability, but including wake effect losses and air density) and to collect the conditions of the study (especially the complexity of the environment).

In order to be able to compare theoretical and effective outputs on the same long term reference period, a correction was applied thanks to the energy indexes to adjust the theoretical value on the standard reference period (2004-2013).

2.4 Analysis of output differentials

Once the effective (i.e. re-evaluated) and theoretical outputs have been adjusted to the same level of availability (100 %) and the same long term reference period, the differences between both outputs are now considered to be primarily associated with the uncertainty on the theoretical study and the uncertainty on the actual performance of the turbines. Therefore, the issue is not of an over- or underestimate of the wind potential of a site, but rather of the over- or underestimate of the actual output capacity of a wind farm.

The output differential is defined as follows:

$$\Delta \mathrm{P} = \frac{Theoretical output - \mathrm{Re}-analysis output}{\mathrm{Re}-analysis output.}$$

<u>N.B.:</u> As a reminder, both outputs include the losses due to wake effects, losses associated with air density and electrical losses. They are based on 100 % availability and are adjusted on the same long term reference.

As the adjustment performed both on the theoretical and effective outputs are subject to uncertainty, the range of -5% to +5% in the output deviation is considered satisfactory. Note that this range is consistent with the range of the uncertainty of power curves guaranteed by the manufacturers.

Thus, the ranges generally considered are:

- -5 % < ΔP < +5 %,

Satisfactory estimation of the actual output capacity of the wind farm

- ΔP > +5 % or < -5%

Respectively overestimation or underestimation of the actual output capacity of the wind farm

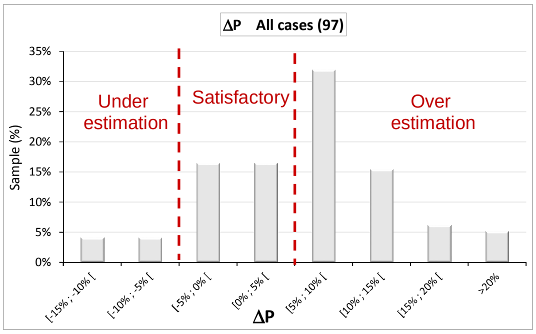
To analyse the link between the difference in measured and estimated outputs and the factors that may affect the accuracy of pre-construction wind potential assessments, several variables were extracted from each report reviewed. These variables are known as "characteristic conditions" of the study. Among the variables extracted, the focus was made on external conditions such as the site environment (complexity of the relief and roughness of the terrain), the height of measurements with respect to the turbine hub height and the distance between the measurement points and the turbines location.

3 Detailed test results

As a reminder, the deviations observed are not related to variations in wind resource over the long term (i.e. theoretical production and measured production adjusted to the same long term period). The output differentials can be explained as the result of the uncertainty on the theoretical wind potential assessment and the uncertainty of the actual performance of the wind farm. The concept of “over-” or “under-” estimation cannot be solely attributed to the site’s wind potential, but is more broadly described as the result of the actual capacities of a wind farm (ie. Resource and performance).

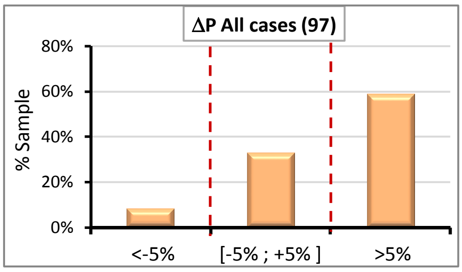
3.1 Global analysis

The histogram below displays the differentials ΔP for the entire set of cases studied:

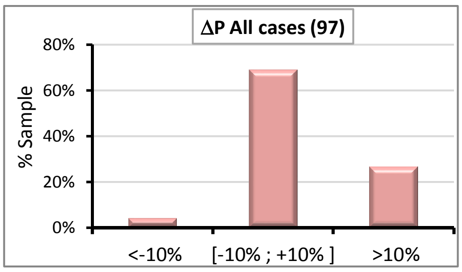


Graph 2 : Distribution of output deviations all projects

The analysis of the differentials can also be presented in the following formats:



Graph 3 : Output deviations inner and outer ± 5 %



Graph 4 : Output deviations inner and outer ± 10 %

From this analysis, the following general points can be highlighted:

- There is a tendency to overestimate the actual output capacity of the wind farms in close to 60 % of the projects considered
- In 1/3 of the cases studied, the differentials ΔP are within the range ±5 % (Equivalent to the uncertainty in the guaranteed power curve)
- In almost half of the cases studied, the differentials ΔP are within a range of ±7 % (Equivalent to the uncertainty in the guaranteed power curve (±5 %) associated with the uncertainty of the theoretical study on the order of ±5 %).
- In more than 2/3 of the cases studied, the differentials ΔP are within the range ±10 %

In order to consider the samples of the study as a portfolio effect, a global ΔP was estimated, accounting for the respective power of each wind farm in the study. The global differential ΔP for the entire set of wind farms in the study is + 5.8 %.

The projects were divided in two sets: the ones corresponding to pre-construction studied carried out before 2004 and the ones issued after 2008. If the global trend to overestimating the actual production capacities is observed in both cases, the studies carried out after 2008 lead to a larger sample of ΔP within the range ±5 %, and to less large deviations (< -10% or >+10 %).

3.2 Parameter-based analysis

Several tests were realized in order to try to identify the influence of the parameters of the projects on the productions deviations.

3.2.1 Main parameters

The following parameters related to the project and the study conditions were considered as the main ones: Site topography, site roughness, height difference between measurement and hub, representativeness of the mast location regarding the turbines.

In order to avoid the combined effect due to separate factors, the following set of combinations were considered to carry out the analysis:

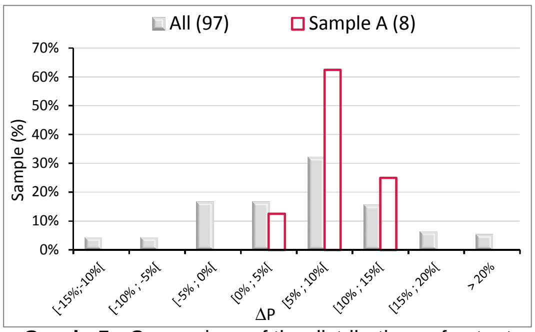
Sample	Topography	Terrain roughness	H_{meas}/H_{hub}	Mast position	No. of cases
All	**All**	**All**	**All**	**All**	**97**
A	Very simple	Very simple	> 4/5	Rep.(*)	8
B	Simple	Simple	> 2/3	Rep.	40
B1	Complex	Simple	> 2/3	Rep.	3
B2	Simple	Complex	> 2/3	Rep.	18
B3	Simple	Simple	< 2/3	Rep.	14
B4	Simple	Simple	> 2/3	Not Rep.	4
B5	Simple	Complex	< 2/3	Rep.	9

(*) Rep. meaning mast position representative of the turbines positions

Tab. 1: Descriptions of the samples analysed

Sample A : Very favourable conditions

The histograms below illustrate the distributions of the ΔP for sample A compared to all cases. This sample corresponds to very favourable conditions to carry out the study (simple topography and roughness, limited or no vertical extrapolation, mast position representative of the position of the turbines location and a satisfactory quality of the installation). Generally, these very favourable conditions of study would lead to a low level of uncertainty in the theoretical study.



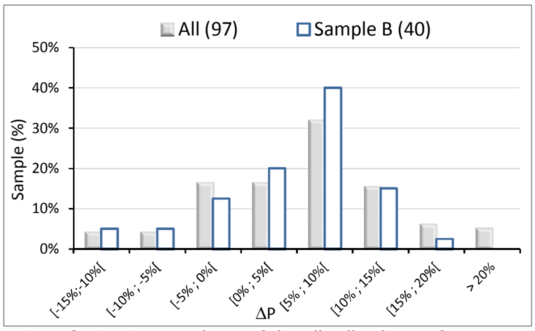
Graph. 5 : Comparison of the distributions of output differentials for all cases and sample A

Only taking into account projects associated with very favorable study conditions still tends on average to overestimate actual output capacities of the wind farms. Although the sample size is reduced, this test highlights that the uncertainty on the turbine performance should be considered.

Sample B: Conditions quite favourable

Sample B allows us to exclude situations associated with known unfavorable characteristic conditions and therefore potentially with a specific source of uncertainty. The distribution of the differentials for this sample serves as the reference for analysing the differentials obtained in further samples. Using this sample as the reference enables to limit the combined effect of separate factors.

The figure below illustrates a comparison of the distributions of ΔP between sample B and the global sample available for this study:



Graph. 6 : Comparison of the distributions of output differentials for all cases and sample B

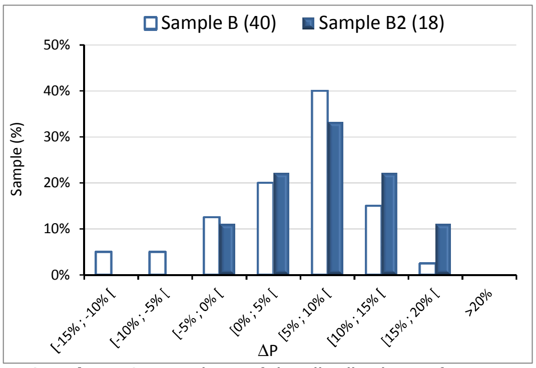
Looking at conditions that are quite favourable (sample B), the distribution of ΔP values is relatively similar to that from the entire set of studies (1/3 of the values are within ± 5% and more than 2/3 are within ± 10%).

Samples B1 and B4

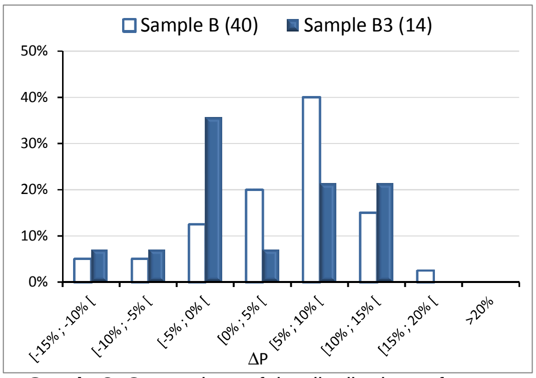
In both cases, the sample size was considered too small (respectively 3 and 4 cases) for interpreting the observed results.

Sample B2 (unfavourable terrain roughness), B3 (unfavourable Hmeas/Hhub) and B5 (unfavourable terrain roughness and Hmeas/Hhub)

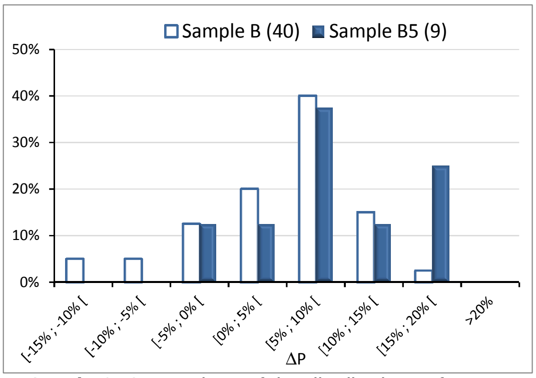
The histograms below illustrate the distributions of ΔP for tests B2, B3 and B5, all compared to the distribution for sample B (quite favourable conditions for all parameters).



Graph. 7 :Comparison of the distributions of output differentials for the ref. sample /Sample B2



Graph. 8 :Comparison of the distributions of output differentials for the ref. sample /Sample B3

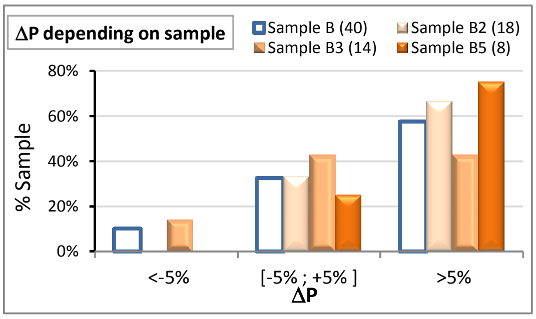


Graph. 9 :Comparison of the distributions of output differentials for the ref. sample /Sample B5

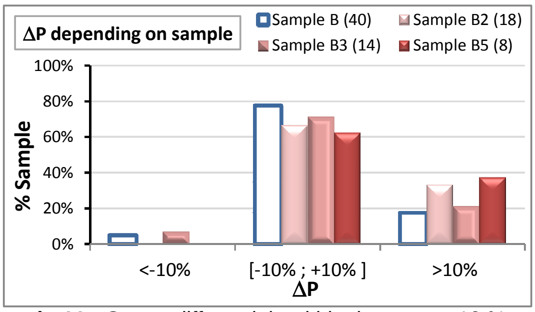
The histograms above reveal that the pre-construction studies involving environments with complex vegetation cover (mostly forest or wooded areas) clearly overestimated the actual output capacities of the operating wind farms. This overestimation is even greater if the set of measurements were taken at relatively low height within complex vegetation cover.

In general, note that pre-construction studies based on measurements heights relatively low compared to turbines hub height tend just as much to underestimate as overestimate the actual capacities of the active wind parks (ie. No specific pattern see graph 8).

Another representation of the results is shown below:



Graph. 10 : Output differentials within the range ± 5 % and beyond, sample Test B / Sample Test B2, Test B3, Test B5



Graph. 11 : Output differentials within the range ±10 % and beyond, sample Test B / Sample Test B2, Test B3, Test B5

3.2.2 Secondary parameters

The secondary parameters used in this study include the model of the cup anemometer, the production capacity level of the wind farm (long term P50 in equivalent hours), the situation of cumulative wake effects and the significant speed differentials between the bottom and the top of a rotor blade.

3.2.2.1 Anemometer model

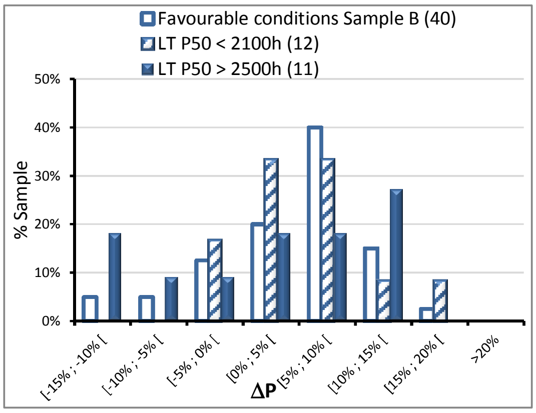
The four most common models of anemometer used in the studies included: NRG, Vector, Thies 1st class and Thies classic. Separating the reference sample by sensors model results in relatively small sample sizes that do not indicate any clear trends. Each project developer also tends to prefer a specific anemometer model, such that the representativeness of the sample is limited and conclusions are therefore difficult to make.

3.2.2.2 Production capacity of the wind farm

The distribution of ΔP was analysed depending on the production capacity of the wind farms based on the re-evaluated output.

Long term P50 (eq. hours)	No. of cases
<2100 h	12
Between 2100h and 2500h	17
>2500 h	11
Total (favourable cases)	40

Tab. 2: Distribution of samples by number of eq. hrs

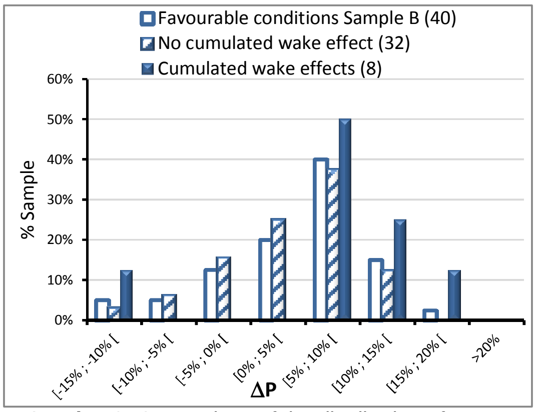


Graph. 12: Comparison of the distribution of output deviations depending on the production capacity

As expected, wind farms with the lowest output levels also have the highest probability of having overestimated their actual output capacities. Interestingly, wind farms with effective output levels above 2500 h do not appear to be associated with more under- or overestimates of actual output capacity. These observations should be noted with caution, as the sample is relatively small.

3.2.2.3 Cumulative wake effects

In order to analyse the differential ΔP between theoretical and measured output for wind farms with a situation of cumulative wake effects, cases when at least 4 turbines are aligned in the prevailing winds direction were looked at separately from the reference sample (favourable conditions– test B).



Graph. 13: Comparison of the distribution of output differentials with and without cumulated wake effect

Note that projects subject to cumulative wake effects are generally associated with overestimation of their actual output capacity (conclusion made with caution, due to relatively small sample size).

3.2.2.4 Significant speed differentials between the bottom and the top of the rotor

Because the measurements for the turbines power curve calculation were carried out in classical environmental conditions (simple topography and terrain roughness), another test was performed to account for significant differentials between the wind speed at the bottom versus the top of the rotor. Such is the case, for example, at sites that have very rough terrain (forests or wooded areas), that require modelling a height displacement and that are associated with turbines with large rotor diameters relative to the hub height. Thus, a complex environment ensures that the situation does not correspond to conditions similar to those in which the power curve was measured.

For this analysis, projects that met the following criteria were considered:

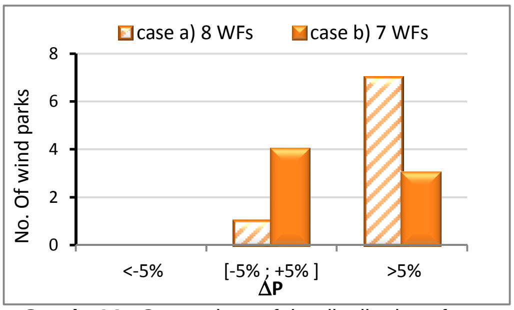
- Complex vegetation cover requiring a height displacement for the simulation,
- Simple topography, ratio of measurement height/hub height >0.6, favourable mast position.

This sample thus included 15 wind farms and a distinction was made between those with rotor diameters greater than the hub height and the other ones.

The sample and the main results are presented in the table next page.

Case	Diameter of rotor/Hhub	No. of cases
a)	90/80 ; 90/70 ; 65/45	8
b)	70/80 ; 70/65 ; 65/58 ; 48/65	7
Total		15

Tab. 3 : Distribution of samples as either a) or b)



Graph. 14 : Comparison of the distribution of output differentials between cases a) and b)

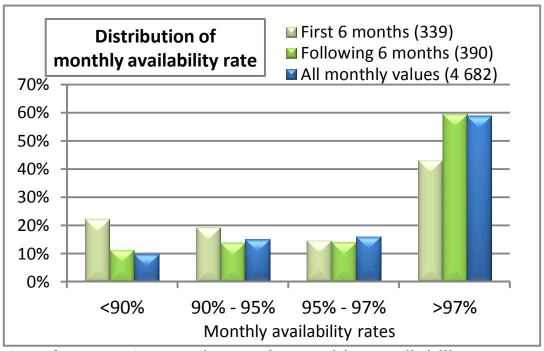
Although the sample size is relatively small, for cases associated with complex terrain roughness (ie. complex vegetation cover) and a rotor diameter higher than the hub height, 7 of 8 wind farms are associated with an overestimation of the actual output capacities.

3.3 Additional results regarding the wind farms availability

The monthly availability rates for the 94 wind farms are summarised in the table below and in the histogram that follows.

Data included	No. of months	Average availability
Entire period	4 682	95.7%
First 6 months of operation	339	92.5%
Following 6 months	390	95.5%

Tab. 4: Distribution of the samples by period (first 6 months, following 6 months 6 and whole period)



Graph. 15: Comparison of monthly availability rates for data associated with the first 6 months of operation, the following 6 months and the entire operational period

The following points can be made:

- The sample represents close to 390 cumulative operational years at the 94 wind parks in the study,
- The average availability rate of the 94 wind parks is close to 96 %,
- Beyond the first 6 months of operation, the monthly availability rates are similar to the rest of the operational period for the wind farms in the study.

A comparison of the monthly availability rates between a set of wind farms isolated in a region that could be difficult to access and a set of wind farms that are concentrated within a radius of 50km in the lowlands has not revealed any significant pattern.

4 Main outcomes

A key point to bear in mind is that these results of output deviations are not related to the wind resource (i.e. theoretical and measured outputs adjusted to the same long term period). The output differentials can be explained on the basis of both the uncertainty on the theoretical wind potential assessment and the uncertainty on the actual performance of the wind farm; the concept of “over-“ or “under-“ estimation is associated not only with the wind potential of a site, but also more importantly with the actual output capacity of a wind farm. Based on the results of this study the following conclusions can be made:

- 1/3 of the wind farms are associated with output differentials that can be considered as satisfactory (within a range of ± 5 %),
- For almost 60 % of the wind farms, there is tendency for the theoretical studies to overestimate the actual output capacity. This overestimation is by more than 10 % for close to 25 % of the wind farms,
- When considering the “portfolio effect” (i.e. looking at all 94 wind farms as a cumulative set), the pre-construction studies overestimate the actual output capacities by approximately 6 %,
- Overall, the distribution of output differentials is the same when each main consultancy is considered separately,

- The probability of greatly overestimating actual output capacity is significantly higher for projects surrounded by complex vegetation cover (i.e. either forested or wooded areas).

- The combination of unfavourable vegetation cover complexity and low measurements heights relative to the turbine hub height leads to an even greater probability of overestimation than the previous situation.

- Only taking into account projects associated with very favourable study conditions (simple topography, simple roughness and measurements height close to hub height), still tends on average to overestimate actual output capacities for the wind farms. Although the sample size is reduced, this test highlights that the uncertainty regarding the performance of the turbines should be taken into account.

- Considering projects with turbines installed in a complex environment (forested or wooded areas) and with a rotor diameter larger than the hub height, in 7 or 8 such cases the output capacity was overestimated. This observation is consistent with the idea of “underperformance”, when the wind speed differential between the bottom and the top of the rotor blade is a significant factor (note the small sample size, however).

4 Conclusions

Apart from considerations about the size and representativeness of the sample, the key finding of this study is the order of magnitude of the output deviations from a significant number of active wind farms in France.

In terms of portfolio effect for the 94 wind farms included in the study, the probability of overestimating the output capacities has largely been covered by the cumulative effects of the decline in the wind resource over the past decade(3) and taking into account a P90 value associated with a level of uncertainty about production capacity of ±10 %.

If the situation is looked at on a farm-by-farm basis, the risk linked to the overestimation of the actual output capacities considering the effects of the decline in wind resource over the past decade is covered:

- for more than 3/4 of the cases associated with quite favourable study conditions, by taking into account the P90 associated with a level of uncertainty on production of ± 12 %
- for close to 90 % of all cases included in the study, by taking into account the P90 associated with a level of uncertainty on production of ± 15 %

In terms of project funding, the method for evaluating risk (4) that takes into account the P90 therefore appears to account for the risk of overestimating actual output capacity. However, an increase in the level of uncertainty on production in pre-construction assessments could be accounted for the following 2 situations:

- a slight increase in the level of uncertainty on production when vegetation cover is complex (forest, wooded areas),

- an increase in the level of uncertainty when vegetation cover is complex and associated with measures at low height and/or a turbine with large rotor diameter relative to hub height.

These considerations must be qualified for sites under development for which additional information is available regarding the actual wind potential of the site (e.g. from other wind farms nearby).

Note that if the error in a wind potential assessment of a wind farm is relatively small on average (close to the uncertainty on the power curve), the fact that it is an overestimate, in the context of the decrease in wind resource over the past decade, should mean that the choice of the long term period has to be considered carefully. Changes in wind resource over the long term can be considered as one of the main sources of uncertainty to date.

[3] *Average long term decrease in the resource in northern France estimated at 6% of production (between the last two decades).*

[4] Note: the considerations above are related to wind resource over periods of 10 consecutive years. Of course, individual years may vary to different extents in terms of output.