Energy yield prediction of offshore wind farm clusters at the EERA-DTOC European project

E. Cantero[3], C. B. Hasager[1], P.-E. Réthoré[1], A. Pena[1], K. Hansen[1], J. Badger[1], J.G. Schepers[2], L.M. Faiella[4], D. Iuga[5], G. Giebel[1], S. Lozano[3], J. Sanz[3],G. Sieros[7], P. Stuart[8], T. Young[8], A. Palomares[9], J. Navarro[9].

[1] DTU Wind Energy, Risø Campus, Roskilde, Denmark, [2]ECN, Petten, Netherlands, [3] CENER, Pamplona, Spain, [4] Fraunhofer IWES, Kassel, Germany, [5]EWEA, Brussels, Belgium, [6] CRES, Athens, Greece, [7] RES, London, United Kingdom, [8]CIEMAT, Madrid, Spain

ecantero@cener.com

National Renewable Energy Centre (CENER), Spain
Wind Energy Department

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Abstract

A new integrated design tool for optimization of offshore wind farm clusters is under development in the European Energy Research Alliance – Design Tools for Offshore wind farm Cluster project (EERA DTOC). The project builds on already established design tools from the project partners and possibly third-party models. Wake models have been benchmarked on the Horns Rev and, currently, on the Lilgrund wind farm test cases. Dedicated experiments from 'BARD Offshore 1' wind farm will using scanning lidars will produce new data for the validation of wake models. Furthermore, the project includes power plant interconnection and energy yield models all interrelated with a simplified cost model for the evaluation of layout scenarios. The overall aim is to produce an efficient, easy to use and flexible tool - to facilitate the optimised design of individual and clusters of offshore wind farms. A demonstration phase at the end of the project will assess the value of the integrated design tool with the help of potential end-users from industry.

This abstracts summarizes the objectives and preliminary results of work package 3. In order to provide an accurate value of the expected net energy yield, the offshore wind resource assessment process has been reviewed as well as the sources of uncertainty associated to each step.

Methodologies for the assessment of offshore gross annual energy production are analyzed based on the Fino 1 test case. Measured data and virtual data from Numerical Weather Prediction models have been used to calculate long term wind speed, wind profile and gross energy.

1. Introduction

The purpose of this paper is to describe the work undertaken and the results within work package 3 (WP3).

The aim of WP3 consists of providing means to produce an accurate assessment of the expected net energy yield from wind farms and clusters of wind farms as well as the associated uncertainty by integrating results from work package 1 (WP1) and work package 2 (WP2).

This work package aims to checking methodologies and techniques used in the assessment of the Net Annual Energy Production of offshore wind farms and the associated uncertainties. Given the lack of available data from operational wind farms it is challenging to validate the proposed methodologies, especially regarding uncertainty quantification which is very case-specific.

2. Test case description: Fno 1

This description has been prepared for EERA-DTOC WP3 activities and presents the main characteristics of FINO 1 research platform, which is situated in the North Sea, approximately 45 kilometres off the Borkum Island (Figure 1), at a depth of some 30 meters. The exact site coordinates are as follows:

N54°0.86´ E6°35.26´

FINO 1 data can be used as test case for estimating Gross Energy in a hypothetical wind farm.

The FINO 1 platform operates unattended under harsh environmental conditions offshore. To meet the different requirements of all users, BSH (Bundesamt für Seeschifffahrt und Hydrographie) provides as much data as they can get. Distorted or abnormal measurements are not excluded as long as it is not proven that they are clearly erroneous. The specifications of the measurement set up provided in this document have been extracted directly from a document sent by BSH. More detailed information about the FINO 1 mast and wind conditions can be found in [1].

Figure 1: Location of FINO1 research platform

2.1 Instrumentation

The database accessible from this website [2] contains the results of comprehensive meteorological and oceanographic measurements made at the offshore test field, as far as they have become operational.

The height of the measurement mast is 100m. Seven cup anemometers are installed at heights of 30 m to 100 m on booms mounted in southeast direction of the mast. One cup anemometer is mounted on top of the mast at 100m height. Three ultrasonic anemometers are present at heights of 40 m, 60 m, and 80 m on north-westerly oriented booms (Figure 2). Additional meteorological measurements consist on wind direction, air temperature, moisture, air pressure and solar irradiation. The oceanographic measurements include waves, wave height, water current and physical properties of the sea water.

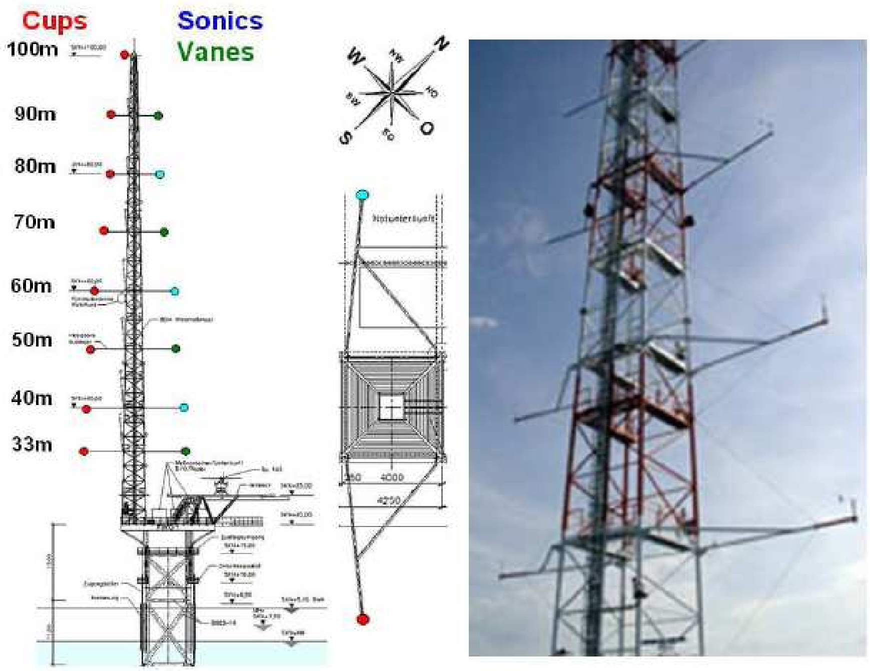

Figure 2: Location and orientation of FINO1 sensors

Mast shadowing effects need to be considered because of the high distortion effects expected from such a large tower on the anemometers. Figure 2 shows the orientation of the sensor booms with respect to the tower. Flow distortion is also present at the top-mounted anemometer since it is surrounded by lighting rods at E, W, N and S directions.

2.2 Input data

The following data was provided for the AEP comparison based on 10-minute averaging period:

- Time series of controlled measured mean, standard deviation and maximum wind speed, mean and standard deviation of wind direction, temperature and pressure.

- Generic power and thrust curves as well for a 2 MW wind turbine, with 80 m rotor diameter and 120 m hub-height, based on an air density of 1.225 kg/m3. For the purpose of this test and to avoid dispersion in air density estimation, the mean site air density shall be assumed to be 1. 225 kg/m3.

3. Methodology

In order to provide an accurate value of the expected net energy yield, the offshore wind resource assessment process has been reviewed (Figure 3) as well as the sources of uncertainty associated to each step.

The gross annual energy prediction (AEP) is derived from either measured or virtual (simulated) wind speed time series at hub-height, U_{hub}, integrated over long-term period together with the power curve from the target wind turbine. Observations need to be filtered out of spurious registers and eventually require vertical extrapolation to hub-height. In the absence of onsite measurements, virtual time series generated by a numerical weather prediction (NWP) model and interpolated to the site and height of interest are used. Long-term extrapolation against historical observational or virtual data is necessary if the original period is of short duration.

The net annual energy production (AEP_{NET}) is the result of applying various sources of energy inefficiency to the AEP, notably: from wind farm wake losses, from electrical losses, from unavailability losses during operation and maintenance (O&M) activities. Wake efficiency is the object of WP1 while the electricity losses are characterized in WP2.

Alongside the process of AEP_{NET} assessment we need to take into account the different sources of uncertainty (Δ) that are propagated in each step. The final outcome of the process is probabilistic with a probability density function defined in terms of the 50, 75 and 90% percentiles (P50, P75, P90). These outputs are used by financial models to calculate the expected return of investment of the project. In brief, the project is more profitable with increasing P50 and less risky with decreasing P90/P50 ratio.

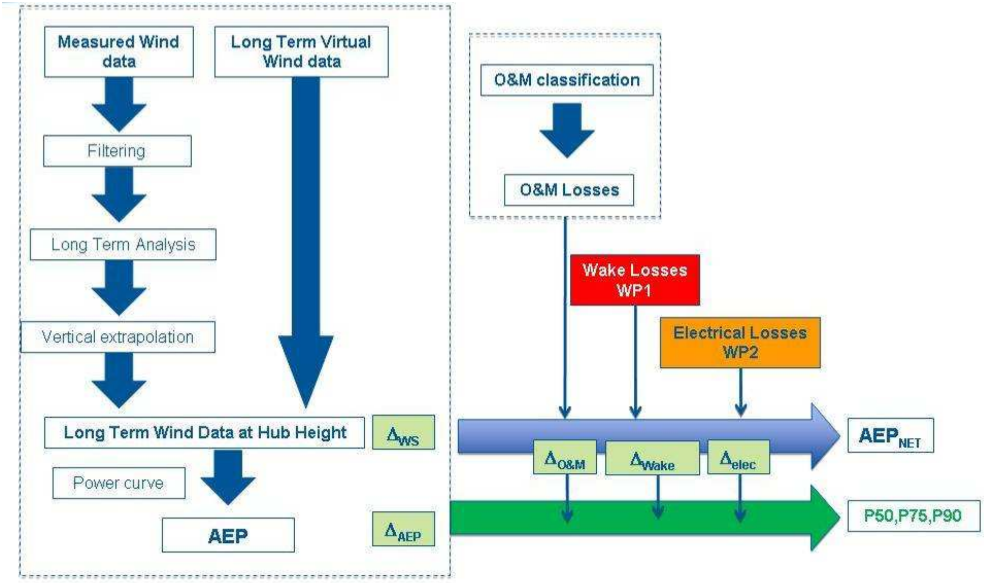

Figure 3: The main components in an offshore wind resource assessment

Based on FINO 1 input data CRES, CIEMAT, RES, Forwind and CENER have estimated the Gross Annual Energy production using own methodologies. To analyze the different techniques in a homogeneous way, the next information has been requested to each participant:

1. For each measured level (100, 90, 80, 70, 60, 50, 40 and 33 m) the mean wind speed for the measured period to make sure that all participants have the same input.
2. To check the filtering techniques and their impact on the results: mean measured wind conditions after filtering: mean wind speed and data coverage for each height level, wind frequency distribution of hours in the year as a function of wind speed and direction for the 100 meters level and mean turbulence intensity at 100 m.
3. Long term wind speed distribution and turbulence intensity as a function of wind direction sector at 100 m level. Long term reference data is not provided as an input such that each participant can use own reference information (meteorological station or virtual data from databases like MERRA, GFS, World Wind Atlas Data…); this will allow assessing the impact from different reference data sources and Measure-Correlate-Predict (MCP) methods of temporal extrapolation.
4. Vertical extrapolation techniques of the mean wind speed and turbulence intensity will be analyzed for a prediction height of 120 meters.
5. AEP will be analyzed based on the long-term prediction of gross energy yield in GWh/year, before wake effects and any other losses.
6. The estimated uncertainty of the long term 10-year equivalent predicted gross AEP, including a breakdown of the individual uncertainty components that have been estimated or assumed.
7. Details of how the particular methodology of each participant, in particular on how the wind speed prediction has been carried out (e.g. MCP technique), if measured or modeled wind shear was used, etc.

To analyze the NWP outputs as offshore virtual masts the gross annual energy production has been calculated based on data from nearest grid point of Skiron mesoscale model simulations.

The wake effects between wind turbines are particularly relevant in offshore environments where long periods of atmospheric stability conditions make the flow recover more slowly than in onshore conditions. This information is obtained from WP1 and it is of great importance at estimating the net energy yield.

Secondly, any cluster of wind farms involves a considerable electrical infrastructure that inherently will produce a certain amount of electrical losses inside each wind farm, between wind farms inside the cluster and between the cluster and the shoreline. The procedure for the estimation of these losses can differ considerably from those at onshore sites and must also be estimated as accurately as possible. This information is obtained from WP2.

Thirdly, an important factor to be included at the net energy yield estimation is the availability of wind turbines and wind farms. Availability of wind farms can be affected by the combination of the vulnerability of wind farm design, weather conditions, wind turbines degradation and maintenance infrastructure. Availability data of wind farms at different scenarios and climatology are not available so a general analysis of percentage yield lost due to weather window accessibility for a range of wind farm parameters has be done in this project.

4. Results

With FINO 1 measured data at different height levels and a power curve as input CIEMAT, CRES, RES, Forwind and CENER have estimated the Gross Annual Energy production.

CENER presents different results, in some steps, obtained by the use of different approaches.

The analyzed results are, the recovery rate and mean wind speed after filtering, the long term mean wind speed, the mean wind speed at hub height, the gross energy (P50) the uncertainties considered and the gross energy (P90).

A summary of the submitted results is given in Table 1 CV is the coefficient of variation.

Table 1: Summary of the results. Recovery rate and mean wind speed only for 100 m level.

Topic	Unit	Mean	σ	Max.	Min.	CV [%]
Recovery rate	%	89.43	9.99	96.55	72.22	11.17
V filtered	m/s	9.88	0.05	9.95	9.84	0.47
LT V	m/s	9.92	0.07	10.03	9.84	0.74
Hub V	m/s	10.08	0.07	10.18	10.02	0.67
TI measured	%	6.35	0.30	6.54	5.82	4.77
LT TI	%	6.38	0.20	6.54	6.05	3.08
Hub TI	%	6.23	0.27	6.47	5.82	4.36
Gross Energy (P50)	GWh	10.00	0.39	10.64	9.46	3.89
Uncertainty	%	5.04	1.91	6.90	1.81	38.00
Gross Energy (P90)	GWh	9.38	0.39	10.14	9.06	4.16

Detailed results of each step are shown in the next points in plots where the y-axis corresponds to the mean value of the submitted results ± deviation. The x-axis shows the number of each team, if no number is given, the result has not submitted by the team.

4.1 Filtering

To check the different filtering criterion used by the companies and their impact in the data set, mean wind speed, wind speed distribution and data recovery rate after filtering has been analyzed.

Figure 4 shows the deviations from the mean value between participants in the recovery rate after filtering in the 100 m level; it is observed large deviations in this value. These deviations are lower in the top anemometer than in the others heights levels with the largest deviations in the 60 m height level, see Figure 5.

This deviations are mainly due to the mast shadow influence and how the filtering of the measurements was performed by each participant, since some participants have eliminated the data affected by this effect (participants 2, 3, 4 and 6) but others have not (participants 1 and 5).

In the case of participant 4 they have filtered only the time period of FINO 1 data without wind farm influence (13 of January 2005 to 14 of July 2009) so the period analyzed by them is different from the others.

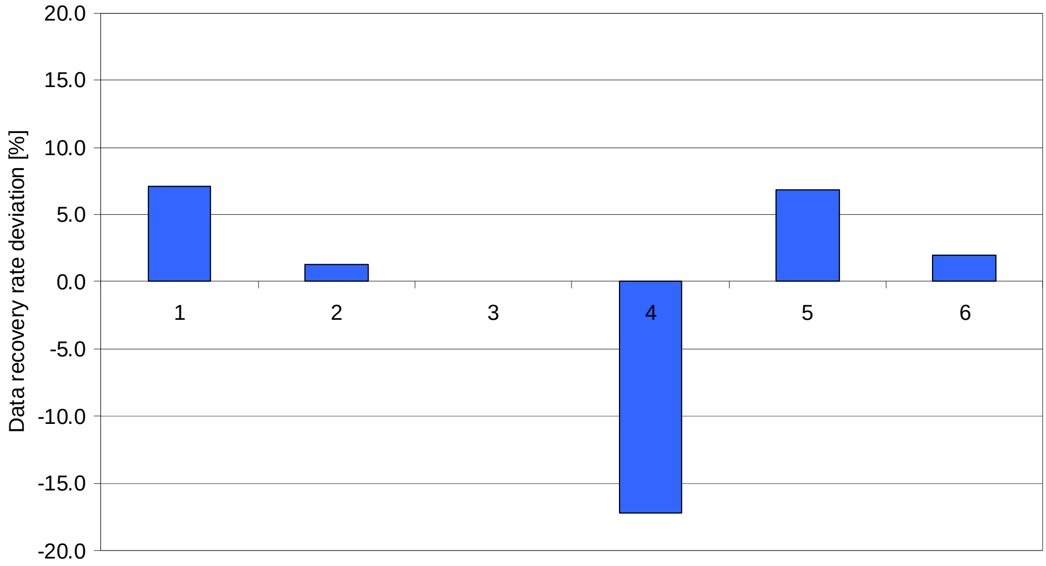

Figure 4: Recovery rate after filtering in the 100 m height level

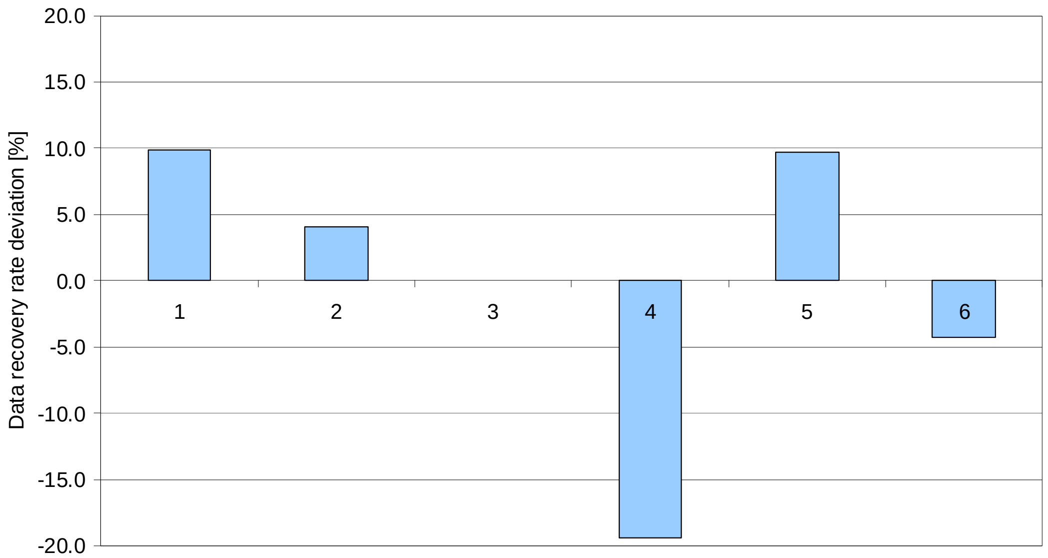

Figure 5: Recovery rate after filtering in the 60 m height level

The influence in the mean wind speed of the filtering process has been analyzed comparing the mean wind speed, obtained by averaging every 10 minutes wind speeds, for the period considered (see Figure 6) with the mean wind speed obtained from frequency distribution of hours in the year as a function of wind speed and direction for the 100 meters level (see Figure 7).

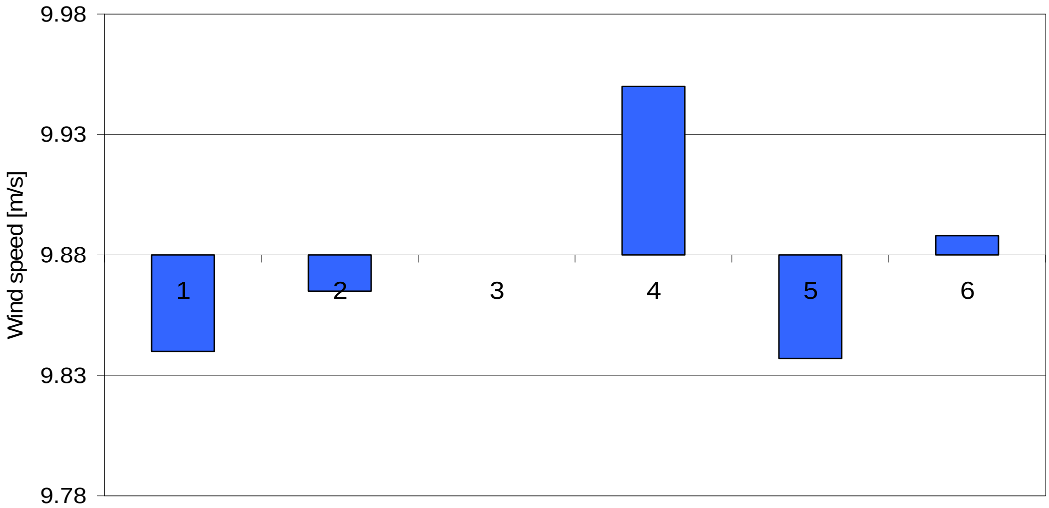

Figure 6: Mean wind speed after filtering at 100 m obtained as mean of ten minutes value. Mean value ± 1.0%

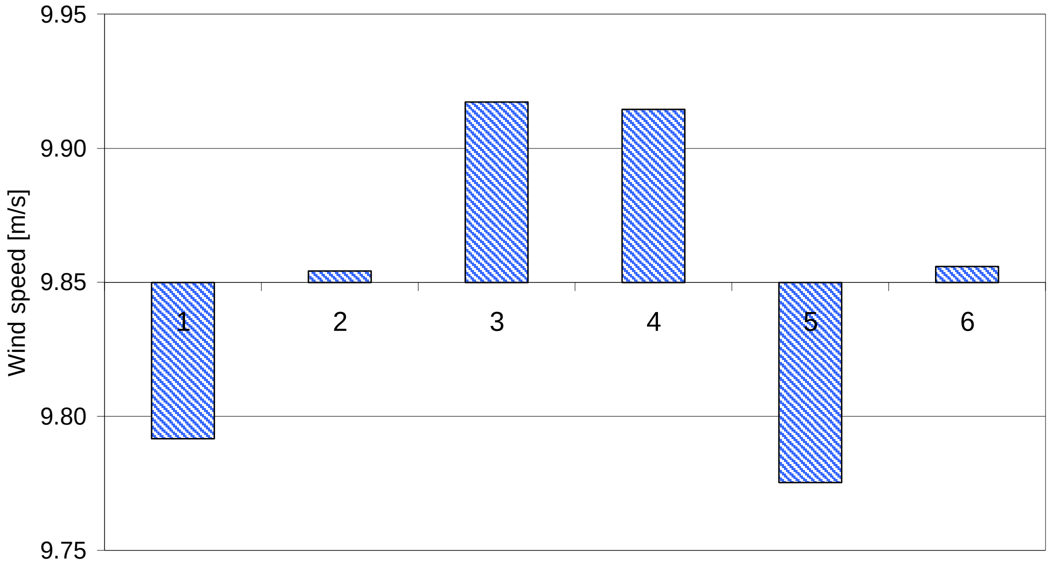

Figure 7: Mean wind speed after filtering at 100 m obtained from frequency distribution of hours in the year as a function of wind speed and direction. Mean value ± 1.0%

The influence of the filtering in the mean wind speed is smaller than expected at least at the top height anemometer. Figure 7 shows higher deviations in the mean wind speed than Figure 6 because the wind direction filtering also affects the mean wind speed derived from frequency distributions.

Figure 8 shows the frequency wind speed distribution at 100 meter and Figure 9 the frequency wind rose for 100 m wind speed taking into account the 90 m wind direction. Some higher deviation in the wind rose is appreciated for participant 4.

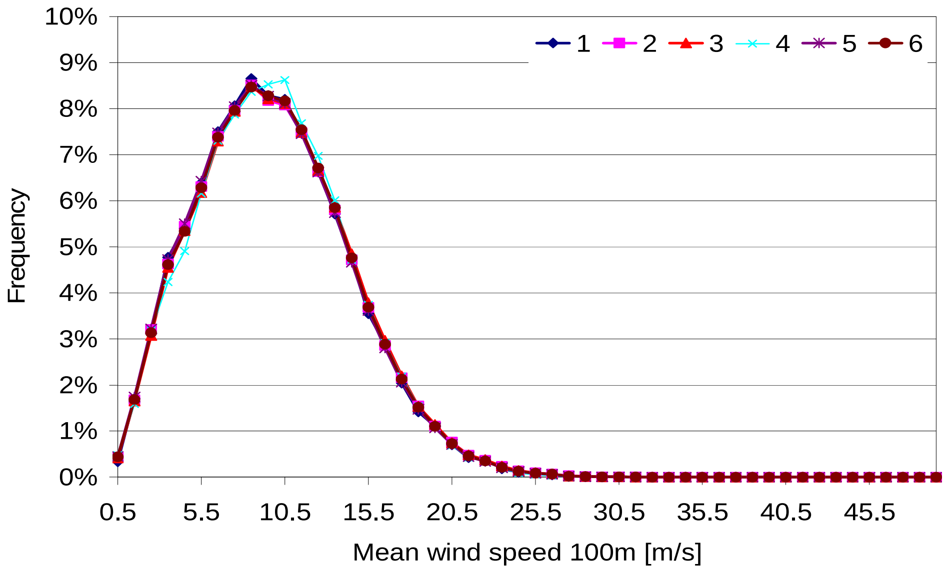

Figure 8: Wind speed frequency distribution at 100 m height level

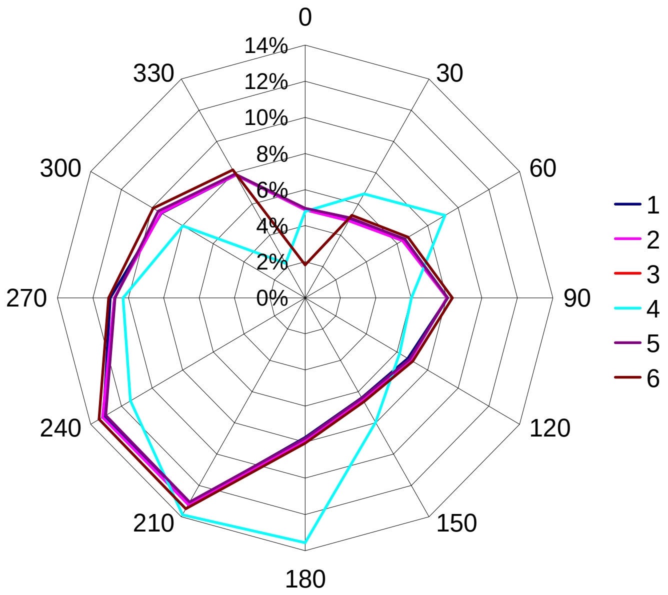

Figure 9: Frequency wind rose

4.2 Long term

The next step considered in FINO 1 test case is the long term extrapolation. For this step the data reference, the long term period and the correlation method followed have been a free decision for each participant.

Table 2 summarizes all the methodologies employed.

Table 2: Summary of long term period, data reference a method employed in Long term extrapolation.

Participant	Long term period	Long term method
1	From Jan 2005 to Dec 2011	No long term correction
2	From Jan 1983 to Dec 2012	Long-term correction based on monthly NCAR data.
3	From Jan 1996 to Jun 2012	Long-term correction based hourly MERRA data as the reference source. A matrix correlation method was used.
4	From Jan 1979 to Dec 2011	Long-term correction based on monthly reanalysis data. The MCP method was applied for 12 different directional sectors.
5	From Jun 2005 to May 2012	No reference.
6	From Jan 1981 to Dec 2012	Long-term correction based hourly MERRA data as the reference source. A lineal correlation method was used.

In spite of the different long term methods, references and periods used the 100 m long term mean wind speed obtained has variations lower than 1.5%, see Figure 10.

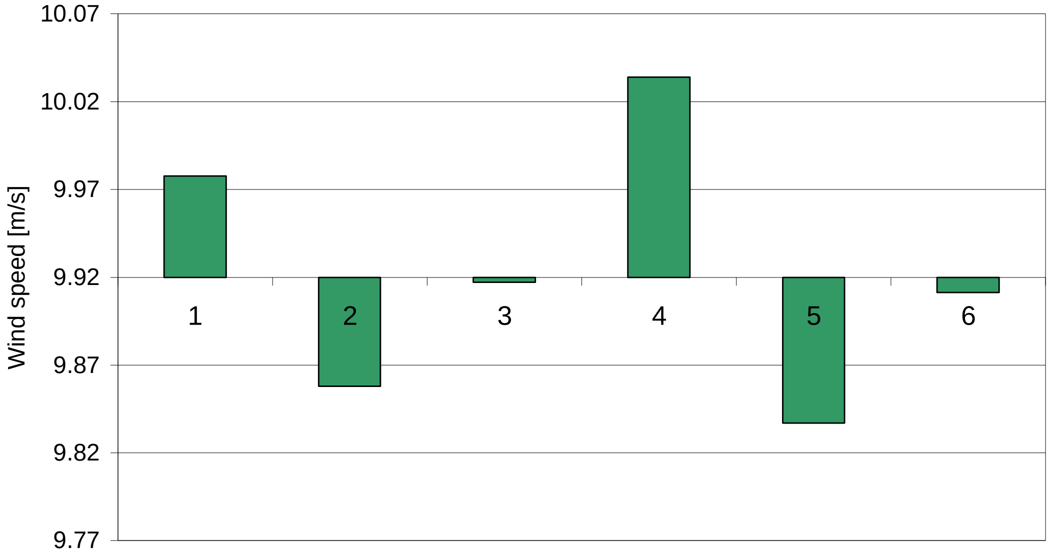

Figure 10: Long term mean wind speed at 100 m obtained from frequency distribution of hours in the year as a function of wind speed and direction. Mean value ± 1.5%

Analyzing the frequency wind speed distribution, see Figure 11, the deviations are higher than in the results obtained after filtering (Figure 8).

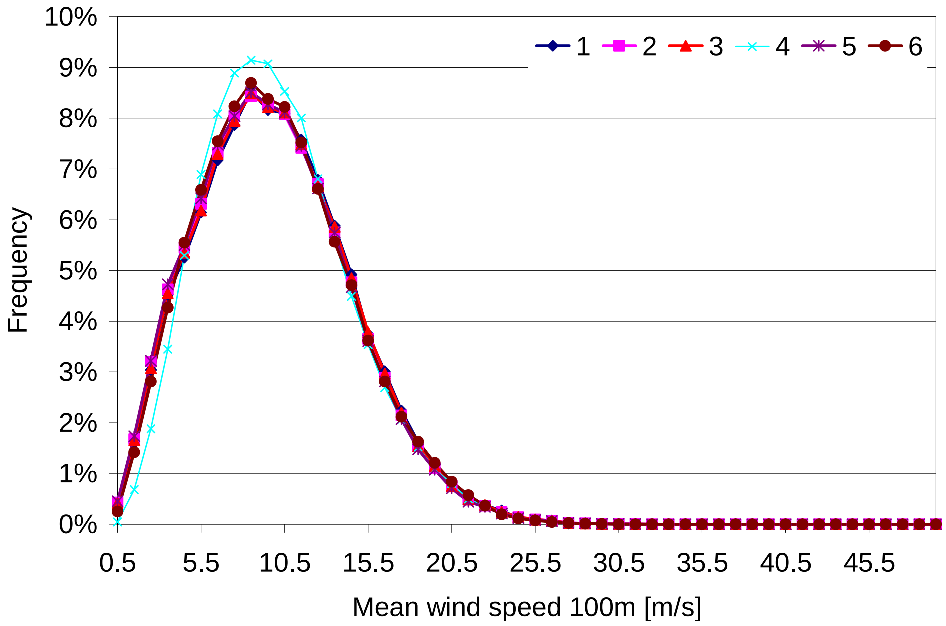

Figure 11: Long term wind speed frequency distribution at 100 m height level

4.3 Vertical Extrapolation

For the vertical extrapolation all the participants have applied the Hellmann exponential law method. Different values of power law coefficient have been obtained but the final hub height mean wind speed has variations lower than 1%, see Figure 12.

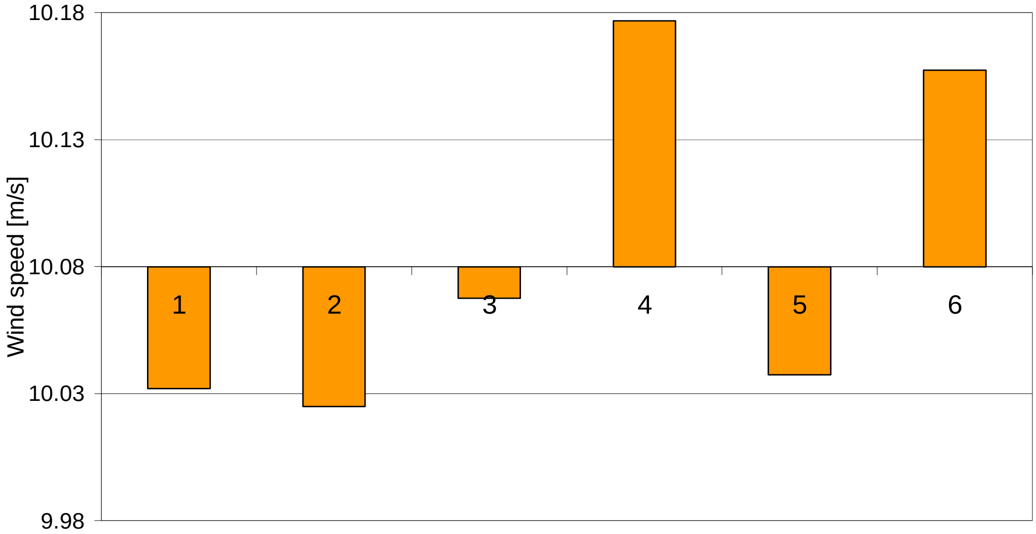

Figure 12: Hub height mean wind speed obtained from frequency distribution of hours in the year as a function of wind speed and direction. Mean value ± 1%

Figure 13 shows the hub height frequency wind speed distribution. It is observed that there are slightly more variations from wind speeds between 5.5 to 12.5 m/s than the one appeared in Figure 11.

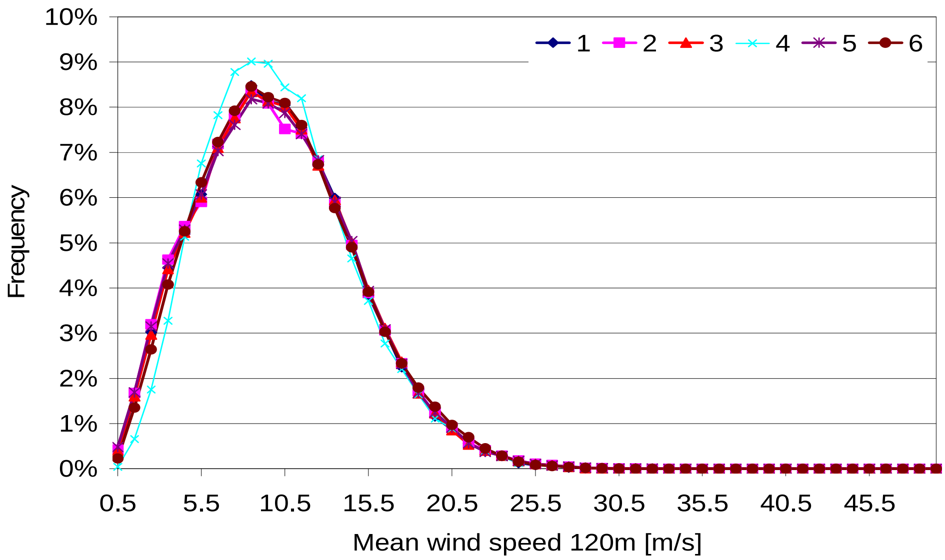

Figure 13: Hub height wind speed frequency distribution

4.4 Gross Energy (P50)

With the hub height long term wind speed distribution and the power curve, according to the methodologies explained by each participant the gross energy has been estimated, and as Figure 14 shows the differences between the results increase to a 6.5%.

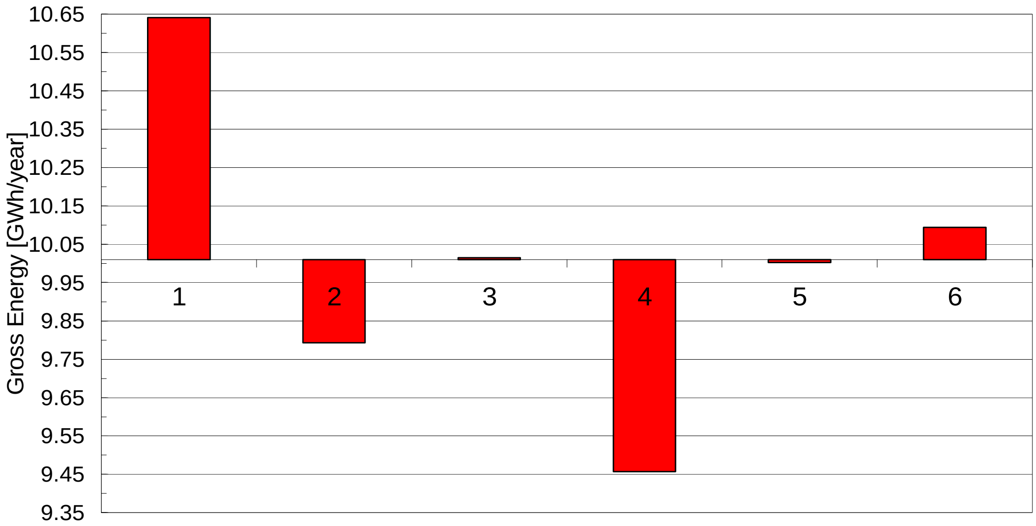

Figure 14: Gross Energy (P50) at hub height. Mean value ± 6.5%

4.5 Uncertainties and P90

The uncertainties that were taking into account in FINO 1 test case by all the participants have been summarized in Table 3. Participant 4 has applied a different methodology to estimate the gross energy so the uncertainties applied are totally different. All most all the participants have considered that there are uncertainties in the Power curve, wind measurements, vertical extrapolation, MCP and time period variability; and all of them have considered that each uncertainty is independent from the others so the final uncertainty is the quadratic sum [3] of all the components uncertainties. A Gaussian distribution of the uncertainty is assumed in all cases.

Table 3: Summary of the uncertainties consider in the gross energy estimation.

Uncertainty/Participant	1	2	3	4	5	6
Wind measurements	X	X	X	-	X	X
MCP	X	-	X	-	-	X
Variability period used	X	X	X	-	X	X
Vertical extrapolation	X	X	X	-	X	X
Power curve	X	X	X	X	X	X
Propagation of power uncertainty for each ten-minute interval to the total energy production	-	-	-	X	-	-
Statistical error for the energy that is calculated from a sample mean	-	-	-	X	-	-
Air density	X	-	X	-	-	-
Future wind variability 10 year	X	-	X	-	X	X

Figure 15 shows the uncertainties values estimated in the gross energy calculation. The incidence of the large deviations in the uncertainty value is translated to the gross energy, P90 value, see Figure 16.

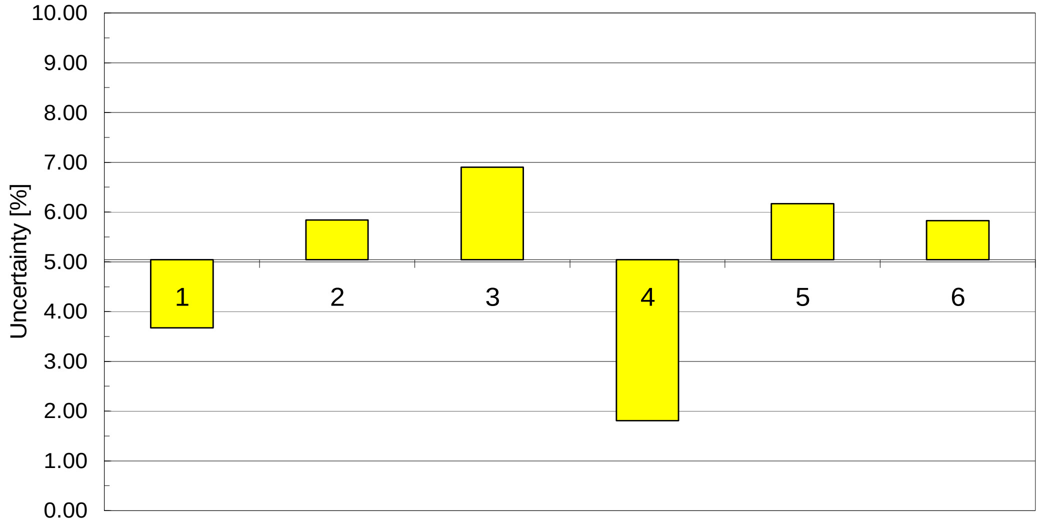

Figure 15: Gross Energy uncertainty as percentage of P50 value. Mean value ± 100%

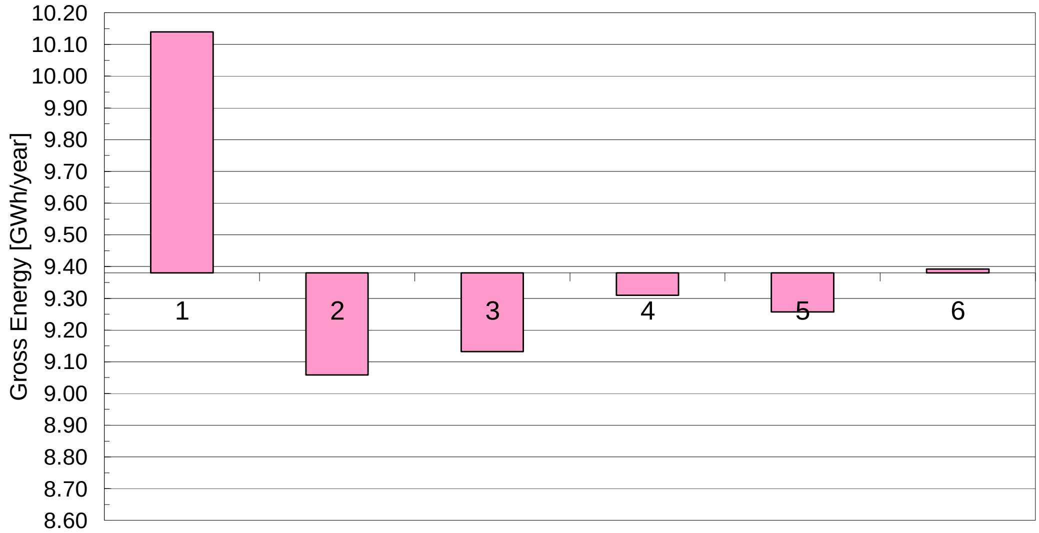

Figure 16: Gross Energy (P90) at hub height. Mean value ± 8.5%

4.6 Results from Skiron virtual mast

As an alternative to the gross energy estimation from measurements, the same calculation has been done with results from a mesoscale simulation, in this case using Skiron hourly outputs from the period comprehended between June 2003 and January 2013.

With this virtual data, both the data filtered and the vertical extrapolation are not necessary in the energy estimation. Long term extrapolation could be done with reference data, or not, because ten years of simulation are available.

Figure 17 presents the gross energy (P50) results including two new results, number 7 is the gross energy estimation with 9 years of Skiron simulations and number 8 is the estimation with 32 years, correlating Skiron data with MERRA data to extend the available time period. Both cases are in the same range than the results obtained with measurements.

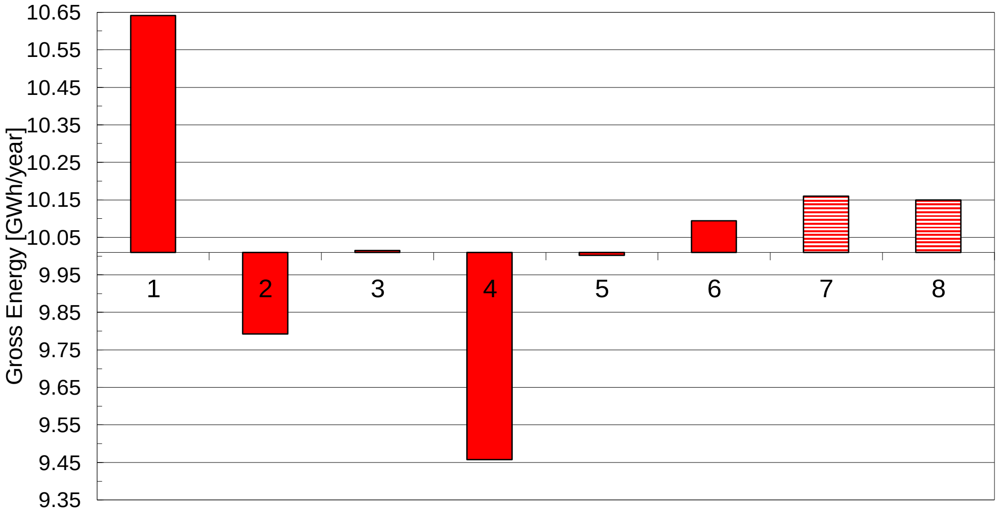

Figure 17: Gross Energy (P50) at hub height. Including results from virtual data, cases 7 and 8. Mean value ± 6.5%

In the uncertainty estimation the measure and vertical extrapolation uncertainty are replaced by the mesoscale model uncertainty. Figure 18 shows the effect in the gross energy P90.

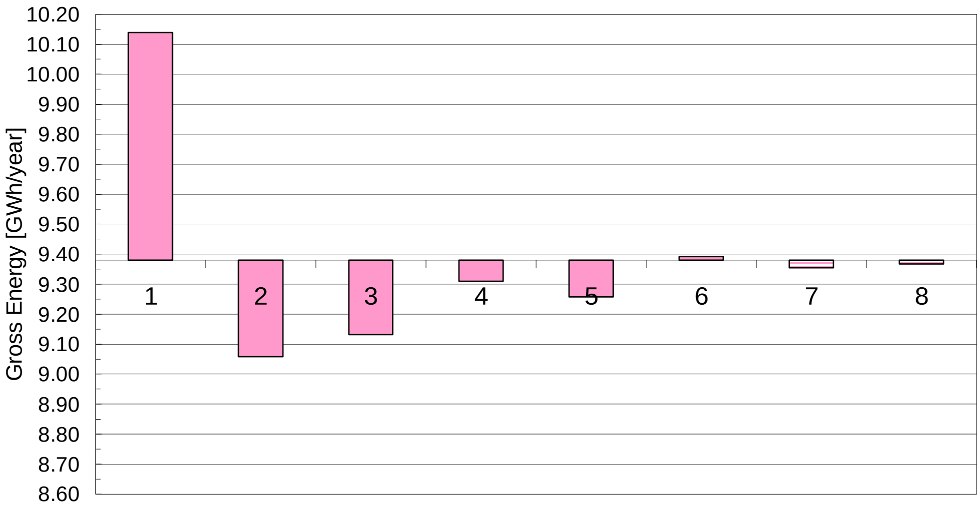

Figure 18: Gross Energy (P90) at hub height. Mean value ± 8.5%

5. Conclusions

According to the steps analyzed in the FINO 1 Gross energy estimation (see Figure 19) some critical points have been detected:

- **Filtering:** the large deviations in the data recovery after filtering, mainly due to the mast shadowing effect show the need to have clear rules to filtered erroneous data especially in the case of mast shadowing influence. The data quality checking should be for all the measure period available and after this with all the relevant information select the full year analysis period.

- **Long term:** a great variety of reference data and long term correlation methods are used, in each case and depending on the quality of the available data a exhaustive long term analysis should be done including validation and uncertainty assessment **¡Error! No se encuentra el origen de la referencia.**.
- **Vertical extrapolation:** everybody has used the Hellmann exponential law that has good results for annual mean values but no when profiles are classified in terms of the observed atmospheric stability [4] and [5], where the wind shear is overestimated during unstable conditions and underestimated in stable conditions. Stability and how it could be applied for wind resource assessment estimation should be analyzed.
- **Gross Energy:** the deviations in the methodologies applied in before steps increasing in the gross energy estimation. According to the results new methodologies, as the explained by FORWIND, should be explored and traditional methodologies should be checked to avoid big discrepancies like in the case of team 1 who with a similar wind speed distribution and the same power curve has obtained higher gross energy than the others participants.
- **Uncertainty:** the sources of the uncertainty are clear but they are not enough to estimate it
- **Virtual masts:** the results obtained for Skiron outputs for the FINO 1 site are very good, but more sites to validate are need to conclude that virtual masts are a alternative for initial offshore wind resource assessment

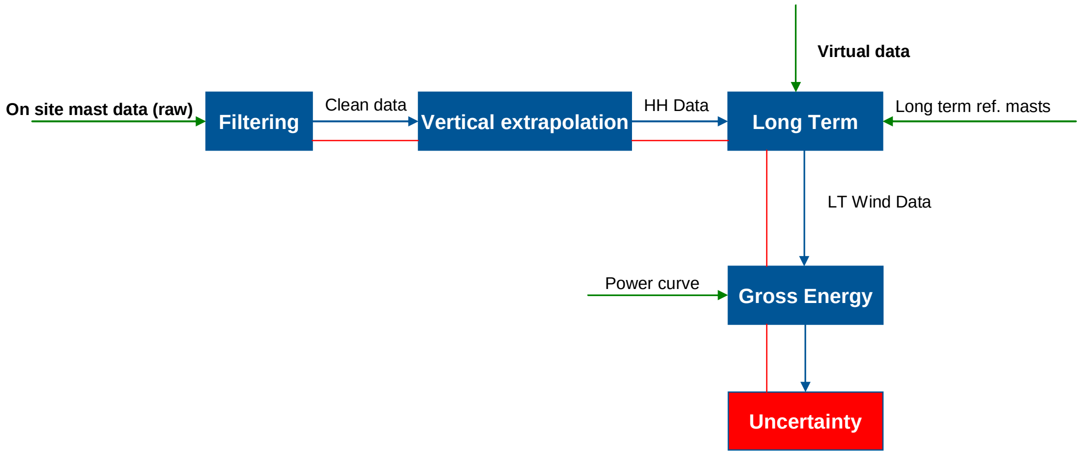

Figure 19: Flowchart of the FINO 1 test case composed of a series of modules (blocks), input data (in green) and exchanged variables (black text on blue arrows). The uncertainty estimation followed up all the process (red lines)

According to these results two conclusions are obtained: first, the need of clear and common methodologies and standards to do the wind energy yield assessment in offshore wind farms and second that the NWP outputs are a good source of information to estimate the offshore wind resource.

Extension of the already started work should be comparing the results of energy yield estimation against real wind farm performance data, including in the analysis the wake losses, the electrical losses and the availability losses. This work could be done either with Alpha Ventus Wind Farm if the wind farm performance data would be available or with Horns Rev.

6. References

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7. Acknowledgement

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