

# Evaluation of the ROMO Wind iSpin Guardian approach

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# Executive summary

ROMO Wind has requested ECN to evaluate its iSpin Guardian approach, which is an approach for wind farm performance monitoring. ROMO Wind's aim is to make wind farm performance more transparent and for this approach to be used in warranty contracts between wind turbine manufacturers and wind farm owners. It is defined in six steps:

1. Determine the power curve of one reference wind turbine according to IEC 61400-12-1.
2. Determine the Nacelle Transfer Function (NTF) for this wind turbine according to IEC 61400-12-2.
3. Determine the nacelle power curve for this wind turbine according to IEC 61400-12-2.
4. Determine the 360° power curve for this wind turbine.
5. Determine the 360° power curve for all wind turbines in the wind farm.
6. Determine the average wind farm Annual Energy Production based on a pre-described Rayleigh wind speed distribution. All turbines that operate according to specifications should have an AEP within 2 % to 3 % of this average.

Currently, often use is made of the traditional, standardized methodology to evaluate the performance of wind turbines in a wind farm based on the IEC 61400-12-1 standard. Although proven technology, it is clear that this methodology has its limitations. Because the wind energy industry is getting more mature and therefore more demanding, new and innovative means appear, to overcome identified limitations. In ECN's view the iSpin Guardian approach is such a new and innovative method to assess the performance of all turbines in a wind farm. ECN has seen promising case studies that would enable wind farm operators to use the iSpin Guardian approach in the first place to identify the status quo of the power performance for the turbine of the wind farm. This already is very valuable in itself.

Next, and more importantly, ECN has investigated to what extent the iSpin Guardian approach can be used in warranty contracts between wind turbine manufacturers and wind farm operators. Such contracts are best made based on standards. Therefore it is noted that the iSpin technology, which is the basis of the iSpin Guardian approach, is incorporated in the IEC 61400-12-2 standard. The obvious potential benefit for the operator is

that he has more means to validate the power performance of the (individual wind turbines in the) wind farm. On the other hand the potential advantage for the wind turbine manufacturer is that he can provide more attractive warranty conditions providing an advantage over competitors.

The most critical aspect of the iSpin Guardian approach, in ECN's view, is the 360° iSpin based power curve, i.e. that the Nacelle Transfer Function is stable when applied in wake conditions. This is the most crucial and potentially most advantageous aspect of the approach. In the cases ROMO Wind presented to ECN, it was indeed shown that the 360° iSpin based power curve provided the same power curve as the iSpin power curve obtained in the undisturbed sector, i.e. according to IEC 61400-12-2. Of course the limitations of the specific cases are acknowledged here.

In order for the iSpin Guardian approach to be adopted in warranty contracts, international and industry acceptance of particularly the aspect of NTF stability in wake conditions is necessary. Industry acceptance can be achieved if this aspect is incorporated in internationally acknowledged recommended practices and/or guidelines as for instance in the framework of IEA Wind, MEASNET and/or IEC. For this, various independent studies should demonstrate under what particular wake conditions (near wake, far wake, multiple wake) the NTF is stable, and preferably why and under what terrain conditions: flat terrain, complex terrain, offshore.

Despite these necessary steps for warranty contract adoption, based on the presented cases ECN believes that the iSpin Guardian approach, as it is at this moment, already is a valuable tool for wind farm operators. The approach is well-suited for monitoring the relative performance of the turbines in a wind farm, which can be used to identify potential performance issues.

# 1

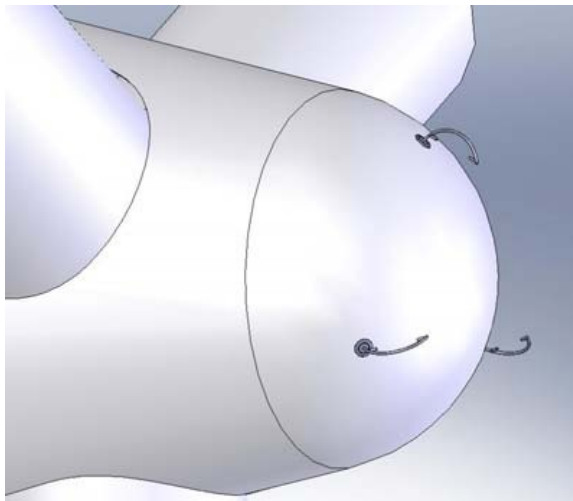
## Background

ROMO Wind requested ECN to evaluate the use of their iSpin Guardian approach: an iSpin technology based wind farm performance monitoring approach to be used in wind farm performance warranties.

### 1.1 iSpin technology

The iSpin system consists of three ultrasonic anemometers, mounted on the spinner of the turbine. The sensors are arranged 120° apart, parallel to the rotor plane, as depicted in figure 1.

**Figure 1:** typical mounting example of the iSpin anemometer



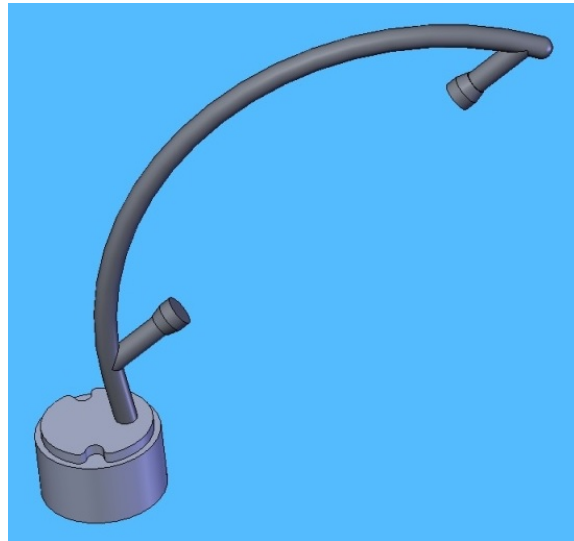
Source: DTU [14]

The iSpin system is an implementation of the more generic patent EP 1,733,241[13] by Troels F. Pedersen from DTU. The patent describes an apparatus for measuring wind speed and direction using one or more sensors directly mounted on the rotor of a wind turbine in front of the blades. According to the patent[13, clause 19] an advantage of a spinner anemometer in general is that it is undisturbed by the turbulence induced by the blades. The added benefit of a spinner anemometer with three sensors, like the iSpin, is that

it can measure the wind speed and directions in three dimensions at each moment[13, clause 25].

The ROMO Wind iSpin anemometry system contains three sonic anemometers, as shown in figure 2. Sonic sensor heads are supplied by METEK, based on their USA-1 sonic anemometers. Each sensor has an accelerometer mounted in its base, which is used for determining the azimuth of the rotor. The system also includes pressure and temperature sensors, which are used to calculate air density, nacelle direction sensor equipment and the required electronics and communication allowing it to operate as a stand-alone system.

**Figure 2:** iSpin sensor



Source: DTU [14]

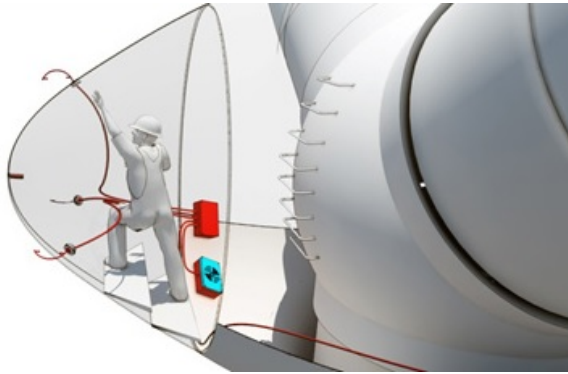
The iSpin calibration is based on extensive research performed at DTU[5]. ROMO Wind, in collaboration with DTU and METEK, provides detailed instructions for the calibration steps[2]:

1. **zero wind calibration** to account for production uncertainties of the ultrasonic sensor
2. **wind tunnel calibration** as required by the IEC 61400-12-2 standard
3. **internal spinner calibration** normalizing the three sensors against each other to account for installation uncertainties
4.  $k_\alpha$  **calibration** after which the iSpin can correctly measure the inflow angle (such as yaw misalignment)
5. **wind speed calibration** after which the iSpin can correctly measure the wind speed. This calibration step involves:
  - a)  $k_1$  **coefficient** representing a linear relation, which accounts for spinner shape and sensor mounting and
  - b) **NTF** representing a non-linear relation accounting for the rotor induction.

The iSpin spinner anemometry is incorporated in the IEC 61400-12-2. The wind tunnel calibration procedure of the iSpin sensor is documented in a clarification sheet[12] published by IECRE, allowing full traceability of the measurement results.

To minimize installation uncertainties, ROMO Wind provides elaborate installation instructions for the iSpin system[1], as depicted in figure 3.

**Figure 3:** mounting of the iSpin components



Source: ROMO Wind [1]

In 2015 DNV GL reviewed[6] the iSpin technology upon request of ROMO Wind. They concluded that the iSpin technology is based on sound theoretical analyses and practical testing.

## 1.2 ROMO Wind

ROMO Wind is a Danish-Swiss technology-as-a-service company with headquarters in Switzerland and operations and offices in Denmark, France, Germany, Ireland, Italy, Spain and the UK. In 2011 DTU sold all rights to the spinner anemometer patent[13] to ROMO Wind, which brought the iSpin to the market in 2013.

ROMO Wind initially focused their iSpin services on yaw misalignment correction. ROMO Wind seeks to expand the application of iSpin anemometry to improve wind farm performance monitoring: the iSpin Guardian approach. In the future ROMO Wind also aims at applying iSpin technology for improving wind farm control and extending wind farm lifetime.



# 2

## iSpin Guardian approach

The iSpin Guardian approach holds the promise of making wind farm performance more transparent. When applied in performance warranties, both manufacturers and farm owners may benefit from increased transparency. In this chapter the iSpin Guardian approach is detailed and offset against the approach followed by present-day warranties. We investigate how the iSpin Guardian approach is founded on IEC standards and for the aspects that go beyond the standards, the claims made by ROMO Wind are identified. Supporting evidence for these claims is provided in the form of case studies performed by ROMO Wind. The results of these studies also provide a sense of accuracy that can be attained with the iSpin Guardian approach.

### 2.1 Description

The iSpin Guardian approach proposed by ROMO Wind aims to set a new standard for power performance measurements of wind farms. This approach requires all turbines in the farm to be equipped with an iSpin anemometer and a meteorological mast (met-mast) to be located near one of the turbines in the farm. This turbine, which should be at two to four rotor diameters from the met-mast according to IEC requirements, is designated as the reference turbine.

The approach encompasses six steps:

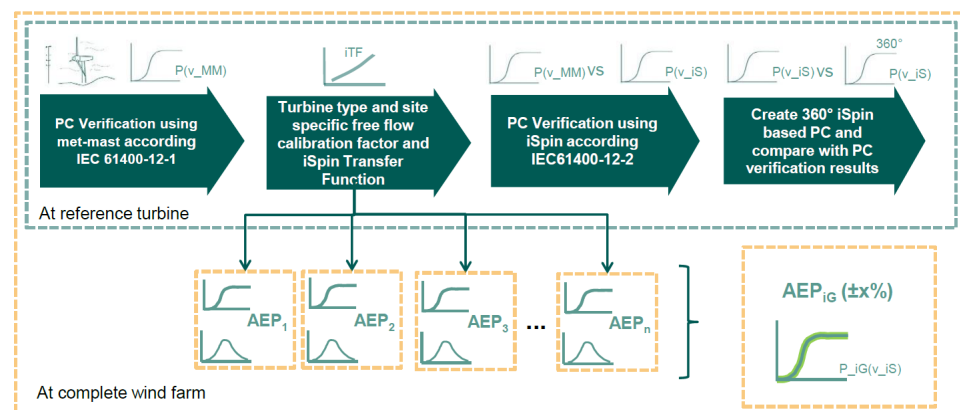
1. A power curve (PC) for the reference turbine is established using the met-mast sensors for the wind measurements in accordance with the IEC 61400-12-1 standard [9]. The result is a power curve for the reference turbine based on the wind speed measured by the met-mast ( $v_{MM}$ ). This power curve is compared directly to the warranted power curve. This step should prove that the reference turbine achieves the warranted performance level.
2. A nacelle transfer function (NTF)<sup>1</sup> is established for the iSpin anemometer of the reference turbine in accordance with the IEC 61400-12-2 standard [10]. The NTF derivation is part of the wind speed calibration (see section 1.1). Together with the  $k_1$  coefficient,

<sup>1</sup> ROMO Wind refers to the NTF as iSpin transfer function (iTF) in figure 4.

it relates the wind speed measurements of the iSpin of the reference turbine to the measurements on the met-mast.

3. The NTF obtained in step 2 is used to produce a power curve according to IEC 61400-12-2. The result is a power curve for the reference turbine based on the wind speed measurement by the iSpin anemometer ( $v_{iS}$ ) of the reference turbine. This power curve is compared against the power curve obtained in step 1. This step should prove that the iSpin based power curve is sufficiently similar to the met-mast based power curve.
4. A similar power curve as in step 3 is produced. However, this time iSpin wind speed data from all wind directions is used, rather than restricting the input data to the undisturbed measurement sector as prescribed by IEC 61400-12-2. The result is the so-called 360° iSpin based power curve for the reference turbine. This result is compared against the power curve obtained in step 3. This step should prove that the iSpin based power curve is not significantly affected by disturbed inflow conditions.
5. The NTF obtained in step 2 is used to produce a 360° iSpin based power curve for each of the wind turbines in the farm. For each turbine the power curve can be combined with the same predefined wind speed distribution to compute the annual energy production (AEP) for that turbine.
6. All 360° iSpin based power curves are combined to yield the average power curve. Finally the mean of all AEP's is computed. Under-performing turbines are identified as those that have an AEP below the computed mean minus a certain percentage.

**Figure 4:** process flow of the iSpin Guardian approach



Source: ROMO Wind [7, figure 8]

The process flow of these steps are depicted in figure 4. The requirements for applying the iSpin Guardian approach are defined by ROMO Wind [7] as listed in table 1.

ROMO Wind claims that the iSpin Guardian approach can verify and monitor the power performance of all turbines in a wind farm. They aim to leverage this ability to enable more transparent warranties between turbine manufacturers and wind farm owners.

## 2.2 Turbine performance warranties

### Warranted Power Curve

In present-day practice, typically wind turbine manufacturers issue a power curve warranty in their Turbine Supply Agreement towards the owner of the wind farm. Normally

**Table 1:** Requirements and data treatment for iSpin Guardian approach

| Requirements                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Data treatment                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"><li>• Turbine should have aerodynamic, symmetrical spinner, because iSpin works under the assumption of near laminar flow on the surface of the spinner</li><li>• iSpin sensors to be installed with maximal tolerance of <math>\pm 1.0</math> cm</li><li>• Usage of wind tunnel calibrated iSpin sensors</li><li>• SCADA data to be used for creating power curve evaluations should be time synchronised to an internet time server with a maximal <math>\pm 3</math> s delay to time server.</li></ul> | <ul style="list-style-type: none"><li>• Turbine must be operated below <math>2^\circ</math> static yaw misalignment, i.e. yaw misalignment should be detected and corrected by use of iSpin in advance</li><li>• Different operation modes have to be treated with different reference characteristics</li><li>• Apply same data treatment on all measurements, i.e. at least:<ul style="list-style-type: none"><li>– Air density correction to <math>1.225 \text{ kg/m}^3</math></li><li>– Turbulence intensity normalization according to 61400-12-1 Ed. 2 (to 10 %)</li><li>– Inflow normalization to horizontal flow</li></ul></li></ul> |

Source: ROMO Wind [7, table 2]

this power curve warranty is valid for two to three years after date of Take Over (construction and commissioning completed). Compensation during this period is only provided if the wind farm owner has performed a Verification measurement. Typically verification must be performed by an independent and mutually agreed consultant and shall be carried out according to IEC 61400-12-1:2005 or recently IEC 61400-12-1 edition 2 and potentially the MEASNET recommendations on a representative sample of the turbines. Power curve verification is therefore not easy to organise by a wind farm owner. This verification will only be performed when several wind turbines are performing sub-optimally, when all technical problems causing underperformance have been taken care of and when a wind farm owner deems it fruitful to do a counter measurement according to the contractually agreed procedures. Many times the ongoing issues and problem solving take up so much time, that the verification measurement cannot be performed within the warranty period for the power curve. For a wind farm owner obviously it is also essential to monitor a potential degradation of power curve performance *after* the warranted period as a very important indicator of wind turbine performance and wind turbine O&M effectiveness. Crudely, nowadays SCADA output is used to monitor power performance.

### Potential benefits resulting from the iSpin Guardian approach

#### 1. Owner's perspective

Having reliable validated power curve performance information which is accepted by the wind turbine manufacturer as being representative for the power curve measurements, opens the door for the wind farm owner

- a) to claim quantified compensation from the wind turbine manufacturer during the power curve warranty period,
- b) to drive the Operations- and Maintenance service provider to better performance, leading to higher/cheaper kWh production,
- c) to gather more high grade information from the correlation between SCADA data and ROMO iSpin Guardian data.

The spinner anemometer, once installed for the iSpin Guardian approach, also provides measurements for yaw misalignment, other flow inclination and turbulence in-

tensity. This data can also contribute to performance optimisation, e.g. by correcting yaw misalignment, and to improvement of wind sector management and wind farm control.

## 2. Wind turbine manufacturer's perspective

- a) Incorporating the iSpin Guardian approach sets the wind turbine manufacturer apart from his competitors who only provide power performance through SCADA data. Providing validated, reliable power performance measurements makes the wind turbine manufacturer potentially vulnerable for wind farm owner's claims in case of underperformance, but definitely also improves wind turbine manufacturer's competitive position in the market in case of consistent overperformance. There are manufacturers that claim smaller deviations from the warranted power curve than their competitors, but are not able to prove that in operating wind farms. With the iSpin Guardian approach that proof has now become available.
- b) Increased transparency towards wind farm owners on actual power performance leads to more optimal wind farm designs and better value for money.
- c) In case of low degradation by wear and tear, manufacturers can distinguish themselves against competitors by measuring higher power performance over operational lifetime.
- d) Having validated, reliable power performance measurements enables wind turbine manufacturers to steer their O&M efforts more effectively, leading to lower cost per kWh, longer lifetime and potential profit sharing with their clients.

## 2.3 IEC standards

Contracts are best conducted based on standards. Like the present-day warranties, the iSpin Guardian approach is founded on the IEC 61400-12 standard. We will review the steps and requirements of the iSpin Guardian approach and how they are related to the IEC 61400-12-1[9] and IEC 61400-12-2[10] standards.

### Step 1

The power curve verification performed in this step is a straight-forward application of the IEC 61400-12-1 standard. However, it should be noted that the prescribed turbulence intensity normalisation first appears in edition 2 of the IEC 61400-12-1 standard[11, annex M], which is still in draft stage, and even then is only designated as 'informative'.

ECN agrees with the data normalization steps. For clarity we would recommend to require that edition 2 of IEC 61400-12-1 be used for this analysis.

### Step 2

The compilation of the wind speed NTF is described in the IEC 61400-12-2 standard.

### Step 3

The computation of the iSpin based power curve and AEP for the reference turbine are a straight-forward application of the IEC 61400-12-2 standard. However comparing of the iSpin based power curve to the met-mast based power curve some of the finer details of the standards need to be taken into account.

IEC 61400-12-2 describes three aspects in which the power curves produced by the IEC 61400-12-2 and 61400-12-1 standards differ:

- the turbine state used for the data selection (IEC 61400-12-1 prescribes to select all data where the turbine was available, while IEC 61400-12-2 further limits this to situations where the turbine was also online.)
- the uncertainty due to influence of terrain effects on the NTF
- the uncertainty due to seasonal dependency of the NTF

The description of the iSpin Guardian approach currently does not specify how these differences are addressed. It may actually be recommendable to disregard the uncertainties mentioned above, because they are intended to provide an uncertainty of the absolute AEP. However, the goal of this step is to provide a comparison between the met-mast based and iSpin based power curves on the same turbine and for the same measurement period. Any such deviations should be described and motivated in the documentation of the iSpin Guardian approach.

#### Step 4

The use of wind speed data acquired outside the undisturbed measurement sector is clearly in disagreement with the IEC 61400-12-2 standard. Although this step could be avoided if the farm layout offers a significant undisturbed sector to all turbines, such as in a line set-up, this step is essential for being able to verify all turbines in a any farm layout.

This step hinges on ROMO Wind's claim that the NTF of an iSpin anemometer is robust in wake conditions. The support for this claim is elaborated in section 2.4.

*"iSpin NTF is robust in wake"*  
(ROMO Wind)

ECN recommends that this step be avoided if possible. In wake conditions the wind speed measured at the hub may not be representative for the whole rotor plane; this is especially true in partial wake conditions. The consequence is that the measurement campaign may be significantly longer for turbines with a small undisturbed measurement sector.

#### Step 5

In this step the NTF obtained for the iSpin anemometer of the reference turbine is reused for the other turbines. The IEC 61400-12-2 standard does allow for this, on the condition that the terrain classification in the farm does not vary too much.

The reservations regarding the terrain classification are included because an NTF may be influenced by the terrain. This is particularly true for devices like a cup anemometer that measure only the horizontal wind speed component, which leads to measurement errors if the terrain slope causes oblique inflow. However, the iSpin anemometer measures the inflow angle (both horizontally and vertically), resulting in ROMO Wind's claim that the iSpin anemometer is unaffected by yaw misalignments or other inflow inclination angles[3, section 1.4]. Differences in terrain may also affect other inflow conditions such as turbulence intensity and wind veer, but these are accounted for by the required data normalisation steps. This leads Wind Solutions to go so far as to conclude[8] that the iSpin anemometer can be used to verify the power curve of any turbine in any wind farm at any time using the calibration derived in flat terrain. The support for this claim is elaborated in section 2.4.

*"iSpin is unaffected by oblique inflow"* (ROMO Wind)

*"iSpin calibration derived in flat terrain can be used to verify PC in any farm"* (Wind Solutions)

Furthermore, ECN recommends to produce iSpin based power curves for the undisturbed sector for the eligible turbines and compare those to the 360° iSpin based power curves obtained in this step. This way the validity of allowing data from wake conditions can be substantiated for each of those turbines, until the NTF stability in wake conditions is proven.

### Step 6

The current approach is to compute the resulting average AEP and define a 'band' of e.g. 2 % to 3 %, which will be regarded as the normal variation. Outliers will be subject for further investigation. While this approach works well for identifying potentially under-performing wind turbines in the current evaluation phase of the iSpin Guardian approach, the question remains how this step will work out when the iSpin Guardian approach is to be used in a performance warranty. It may prove necessary to fix at least the variation band beforehand.

### Requirements

ECN agrees with the requirements and data treatment steps. It would be interesting to add how non-compliance, such as exceeded installation tolerance or yaw misalignment, affects uncertainty.

## 2.4 Nacelle Transfer Function stability

The most crucial aspect of the iSpin Guardian approach is the stability of the iSpin NTF; it plays an important role in steps 5, 4 and, to a lesser extent, 3. The NTF accounts for the influence of the rotor induction on the iSpin measurements. Influences that can affect the NTF are changes to the turbine itself and differences in the inflow conditions caused by other turbines or the terrain. If the NTF is sensitive to these external influences, reusing a previously obtained NTF will introduce significant uncertainties.

Because the measurement of a NTF requires the presence of a met-mast near the wind turbine, it is practically impossible to prove NTF stability for all turbines in a farm. This section evaluates what supporting evidence is available to claim NTF stability.

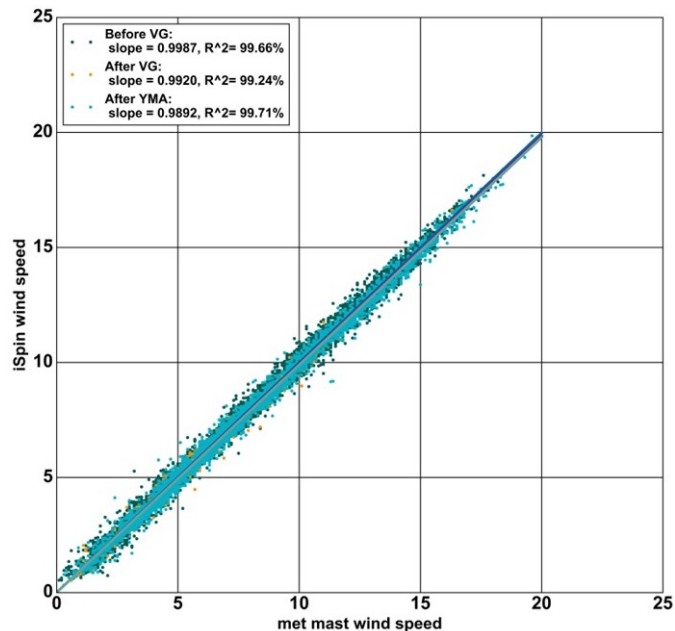
### Turbine

While performing a performance verification, it is highly undesirable to modify the turbine or its control logic. This is covered by the requirements of the iSpin Guardian approach. However, NTF/calibration stability under mildly varying turbine conditions is still relevant for two reasons:

1. As the turbine ages, its condition changes, e.g. blades getting dirty. This affects induction and hence the NTF.
2. When applying the NTF obtained at one turbine for another (of the same type), there will inevitably be minor differences between the turbines. The influence of the spinner shape and sensor mounting are covered by the  $k_1$  calibration. However, in a farm this calibration can only be performed for the reference turbine, because it requires a met-mast as a reference.

ROMO Wind compared wind speed measurements of a met-mast to those of an iSpin anemometer on a turbine what underwent two modifications: applying vortex generators near the blade root and yaw misalignment correction[7]. As shown in figure 5, ROMO Wind demonstrates that the turbine modifications had no significant effect on the relation between met-mast wind speed and iSpin wind speed measurements.

**Figure 5:** Robustness of iSpin measurements concerning turbine modifications



Source: ROMO Wind [7, figure 4]

The robustness after application of the vortex generators is a positive result. Of course, if such a modification is performed on a farm being monitored using the iSpin Guardian approach, it should still be recommended to renew the NTF. It would be interesting to see a similar comparison for the same turbine with clean and dirty blades.

The robustness after yaw misalignment correction is not surprising, because of ROMO Wind's claim that the iSpin is unaffected by oblique inflow. Note that yaw misalignment correction before applying the iSpin Guardian approach is still a requirement. However, this need originates from the negative effect misalignment has on the power production, not from the iSpin wind speed measurements.

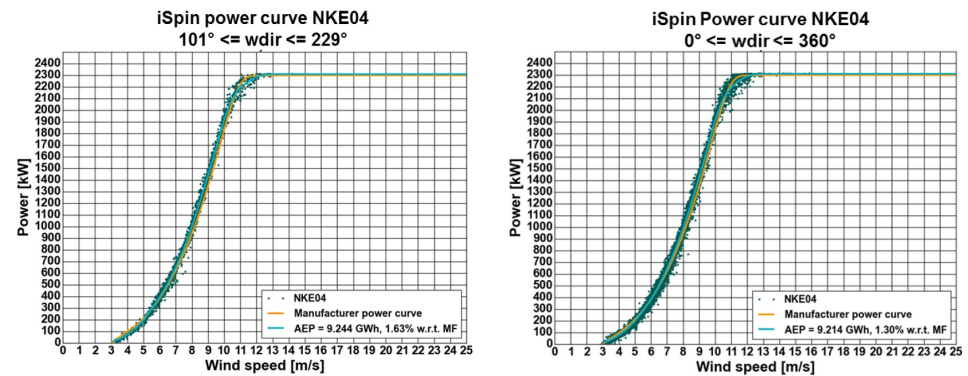
## Wake

Demonstrating robustness in wake conditions by directly comparing wind speed measurements is hard to do. A met-mast is not a valid reference in wake conditions. Therefore step 3 and 4 of the iSpin Guardian approach are used by ROMO Wind as an indirect robustness test. The iSpin based power curve of a turbine is computed for two datasets: the first only contains wind speed data obtained from the unobstructed measurement sector and the second contains all measurements. If the two resulting power curves are comparable, so were the wind speed measurements.

ROMO Wind performed a three month experiment at the Danish Nørrekær Enge (NKE) wind farm. This farm consists of 13 turbines in a line set-up in flat terrain. The test was

performed at turbine NKE04. The results are presented in figure 6. Wind Solutions concludes that the power curves are almost the same[8].

**Figure 6:** iSpin power curve in wake conditions; left: undisturbed measurement sector only, right: 360°



Source: ROMO Wind [7, figure 3]

ECN recognises this as an impressive result, but more extensive testing is needed to prove robustness of the NTF in wake conditions. It would be interesting to further inspect the effect of undisturbed, wake and partial wake inflow conditions on the 360° power curve. This could be achieved with a sector-wise NTF. If 10-minute averaging causes high wind direction variability, using short-term averaging may prove necessary.

It would also be valuable to compare the iSpin based results against those obtained with competing nacelle anemometry such as IEC61400-12-2 calibrated cup anemometer or a (3D) nacelle lidar.

## Terrain

Because modifying the terrain is difficult, proving NTF robustness in varying terrain is best achieved by deriving an NTF for identical turbines in various terrains. However, this requires that a met-mast be present at each of these locations too. Therefore ROMO Wind used the power curve comparison technique that is also applied for testing NTF robustness in wake conditions.

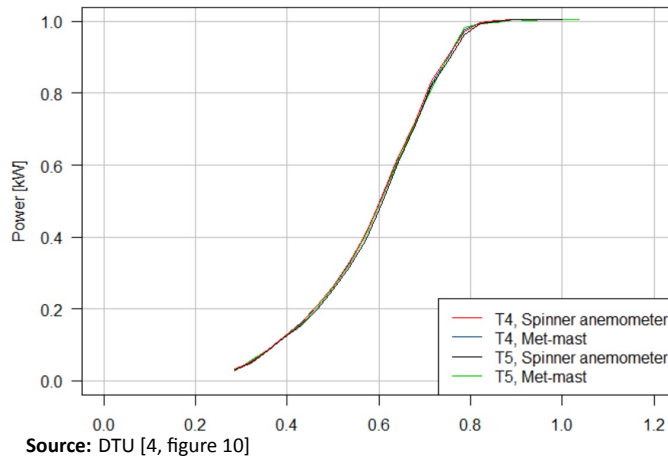
DTU performed an analysis for two turbines (T4 and T5) of the NKE wind farm that are both close to the same met-mast[4, section 8]. The NTF obtained for the reference turbine T4 was reused for the computation of the iSpin based power curve for T5. The (undisturbed sector) iSpin based power curves were compared against the met-mast based power curves. While the results, presented in figure 7, are excellent, the terrain variation between two adjacent turbines in flat terrain is negligible.

In a different analysis, the undisturbed measurement sector of 10 turbines<sup>2</sup> of the NKE wind farm were compared, as shown in figure 8. The power curves agree nicely. However, this should be considered a best-case, yet realistic scenario: the farm is located in flat terrain, the NTF was established in the same farm and all turbines have an undisturbed measurement sector.

A second test was performed at a Swedish wind farm, consisting of 40 turbines in wooded, semi-complex terrain. This time an NTF was used that was obtained during a campaign

<sup>2</sup> Three other turbines were derated. Also, turbine NKE01 should be disregarded for having a slightly different sensor configuration.

**Figure 7:** Comparison of iSpin and met-mast based power curves of the NKE farm



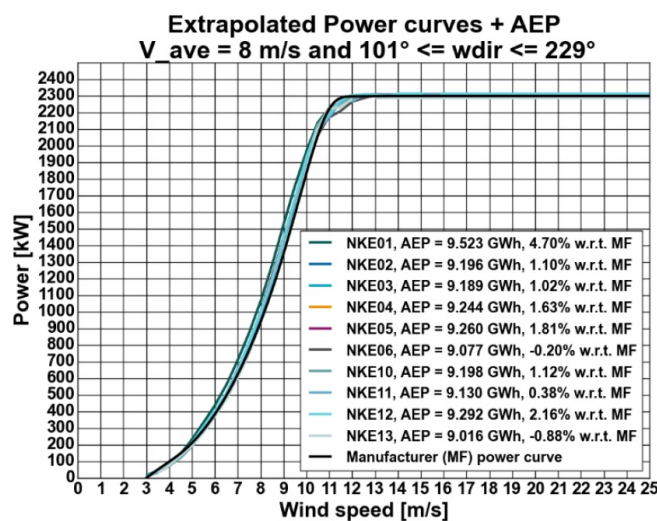
on the same turbine in flat terrain in Spain. In spite of these complicating factors, the resulting power curves shown in figure 9 agree nicely once more. The curves form two groups, because 11 turbines were derated.

For both the 29 turbines operating at nominal power and the 11 derated turbines, the same NTF was used. This was done because only a single NTF was available (from a different site). It should be noted that according to the iSpin Guardian approach requirements, a different NTF should have been established for the derated turbines.

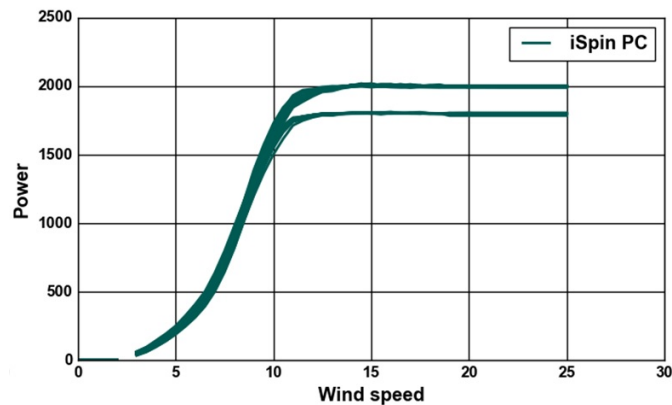
It would be interesting to produce iSpin based power curves using undisturbed sector data only, for eligible turbines, so terrain influence may be observed separately from the wake influence.

A third test was performed at an offshore wind farm. Three turbines were equipped with iSpin anemometers. The resulting 360° power curves show very good agreement.

**Figure 8:** Undisturbed sector iSpin based power curves for 10 turbines of the NKE wind farm



**Figure 9:** 360° iSpin based power curves for a wind farm of 40 turbines in semi-complex terrain



Source: ROMO Wind (unpublished)

## 2.5 Accuracy

In the previous section global results of case studies were presented that, at the very least, instil a sense of confidence in the validity of ROMO Wind's claims that are required for the iSpin Guardian approach. In this section the results related to the accuracies found in these case studies are presented.

### Wind speed

An extensive iSpin uncertainty analysis was performed by DTU[15, 4]. The measurement uncertainty for a fully calibrated iSpin anemometer was assessed according to the IEC 61400-12-2 standard. Based on test data from the NKE wind farm, the total uncertainty in the horizontal wind speed was computed to be 3 % to 4 %[15, fig. 48].

When the NTF obtained on the reference turbine is used on another turbine, the most important additional uncertainty - in the flat terrain of the NKE farm - is caused by the mounting accuracy of the iSpin sensors (on the new turbine). The mounting accuracy was determined to be  $\pm 2$  cm, giving rise to an additional wind speed uncertainty contribution<sup>3</sup> of 1.2 %[4, fig. 18].

### Annual energy production

The uncertainty of the AEP is the result of two sources: the uncertainty of the power measurements and the uncertainty of the wind speed measurements. If the wind speed measurement is performed with a met-mast, the methodology is described in IEC 61400-12-1 standard. If the wind speed is performed with a nacelle based anemometer, such as the iSpin, the IEC 61400-12-2 standard should be followed.

In a study of the reference turbine of the NKE farm the iSpin based AEP was compared against the met-mast based AEP. "For a hub height annual average wind speed of 8 m/s, the AEP uncertainty in the spinner anemometer power curve was found as 5.6 % of the measured AEP; while for the met-mast it was 4.4 % of the measured AEP." [15]. In this analysis uncertainties related to seasonal variation and terrain influence on the Nacelle

<sup>3</sup> Note that these uncertainty contributions are added in quadrature.

Power Curve (NPC) were not taken into account. This test is representative for the power curve comparison in step 3 of the iSpin Guardian approach.

In step 5 the NTF of the reference turbine is reused for all other turbines. The two-turbine comparison at NKE, as shown in figure 7, is most representative for this step. This study concludes that “under the condition that the mounting of the sonic sensors are very similar to the reference mounting, power performance measurements with use of spinner anemometer can be made within 0.38 % difference in AEP for an annual average wind speed of 8 m/s.”[4]

Finally, in step 6 of the iSpin Guardian approach the AEP of all turbines are compared. This analysis was performed for 9 turbines of the NKE farm and 29 turbines in a Swedish wind farm.

The results of the three-month campaign at the NKE farm in flat terrain are shown in figure 10. All turbines have a computed AEP within 2 % of the mean, except for turbine T13. Analysis of the iSpin anemometer data indicated this turbine has a static yaw misalignment of 6.8°.

**Figure 10:** 360° iSpin based AEP for 9 turbines in the NKE farm

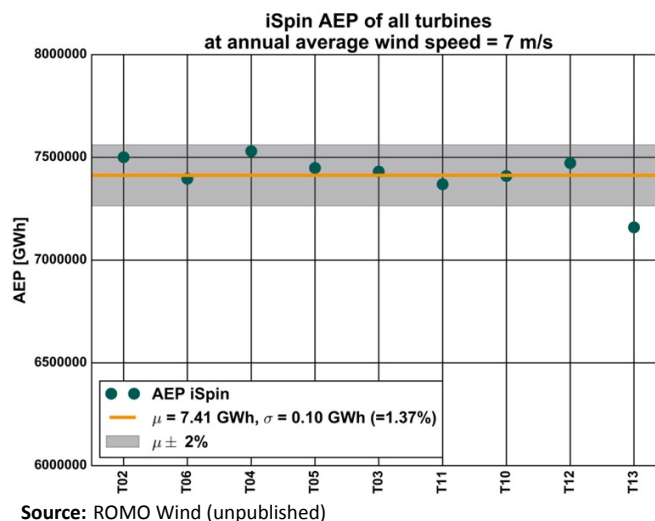


Figure 11 shows the results of the one-year campaign at a Swedish farm in semi-complex terrain. In spite of the terrain complexity and the use of a NTF from a different site, the computed AEP values for the 29 turbines<sup>4</sup> are almost confined by the (arbitrarily chosen)  $\pm 2\%$  interval around the mean value.

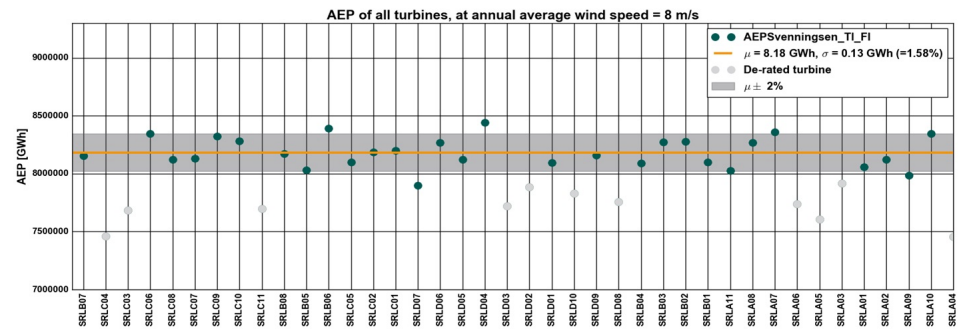
It should be noted that the results in figure 11 are based on power curves for which the air density normalization proposed by Svenningsen[16] was applied, instead of the IEC 61400-12-2 prescribed normalization<sup>5</sup>.

In a warranty contract the wind speed distribution will be prescribed. However, to gain insight into how well the power curves compare, it would be interesting to compute the

<sup>4</sup> The AEP values for the 11 derated turbines are shown in figure 11, but not taken into account for computing the mean AEP.

<sup>5</sup> By contrast, in figure 9 the power curves obtained with the IEC 61400-12-2 normalization method are presented.

**Figure 11:** 360° iSpin based AEP for 40 turbines in a Swedish farm



Source: ROMO Wind (unpublished)

AEP variation for several Rayleigh wind speed distributions.

# 3

## Conclusions

ECN has evaluated ROMO Wind's iSpin Guardian approach for wind farm performance monitoring. In this section the main conclusions of ECN's evaluation are provided.

### 3.1 Guardian approach evaluation

Currently, often use is made of the traditional, standardized methodology to evaluate the performance of wind turbines in a wind farm based on the IEC 61400-12-1 standard. Although proven technology, it is clear that this methodology has its limitations, one of which is that only one or a selected number of turbines can be assessed in a wind farm and at significant cost and effort. The wind energy industry is getting more mature and therefore more demanding. In this developing industry new and innovative means appear that can overcome identified limitations. In ECN's view the iSpin Guardian approach is such a new and innovative method to assess the performance of *all* turbines in a wind farm.

Based on the promising case studies presented, ECN believes the iSpin Guardian approach can be used to monitor the performance of all turbines in the farm relative to one another. This is already very valuable in itself. It enables wind farm operators to use the iSpin Guardian approach to identify the status quo of the wind farm, identify potential performance issues and monitor performance degradation.

Next, and more importantly, ECN has investigated to what extent the iSpin Guardian approach can be used in warranty contracts between wind turbine manufacturers and wind farm operators. Such contracts are best made based on standards and in that sense it is noted that the iSpin technology, which is the basis of the iSpin Guardian approach, is incorporated in the IEC 61400-12-2 standard. The obvious potential benefit for the operator is that he has more means to validate the power performance of the (individual wind turbines in the) wind farm. On the other hand the potential advantage for the wind turbine manufacturer is that it can provide more attractive warranty conditions providing an advantage over competitors.

The most critical aspect of the iSpin Guardian approach, in ECN's view, is the 360° iSpin based power curve, i.e. that the Nacelle Transfer Function (NTF) is stable when applied

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in wake conditions. This is the most crucial and potential most advantageous aspect of the approach. In the cases ROMO Wind presented to ECN, it was indeed shown that the 360° iSpin based power curve provided the same power curve as the iSpin power curve obtained in the undisturbed sector, i.e. according to IEC 61400-12-2. Of course the limitation of the specific cases is acknowledged, here. In this respect clear steps ahead are defined and those are discussed below.

The Guardian approach is defined in six steps of which the steps 1, 3 and 4 are to determine a power curve: (1) Power curve according to IEC 61400-12-1, (3) Power curve according to IEC 61400-12-2 and (4) 360° iSpin power curve. Although the purpose of each step has been made clear by ROMO Wind, ECN identifies that each step is a potential source of dispute on clarity and/or deviations. In this respect ECN advises to clearly value each step on the added value. More particularly, as steps 3 and 4 are essential for the iSpin Guardian approach, it may be worthwhile to omit step 1 in the approach.

A subtle remark is that currently the iSpin Guardian approach comprises power measurements based on SCADA data, whereas IEC 61400-12-2 (and IEC 61400-12-1) requires power measurements with calibrated devices. Although this equipment is relatively easy to implement, it does mean that the approach requires additional instrumentation and periodic calibration effort.

## 3.2 Steps ahead

The iSpin Guardian approach, in its present form, is discussed above. From this discussion clear steps have been identified by ECN to improve the approach and make it ready for market entry as it was intended.

It was already noted that the iSpin technology is incorporated in the IEC 61400-12-2 standard. Still, in order to be fully compliant and for full standardization of this technology clarification sheets and uncertainty components need to be addressed. ECN has seen that ROMO Wind is aware of these points and is taking full action to cover these points in the near future.

ECN has taken ROMO Wind's paper "*Holistic performance monitoring of wind farms - the iSpin Guardian approach*"[7] as the explanation of the iSpin Guardian approach. Based on the drafting of this report, ECN advises ROMO Wind to clearly describe the approach in detail, some of which is lacking in this paper. A clear and thorough description of the approach will help in standardizing the approach and in incorporating it in warranty contracts.

ECN advises ROMO Wind to clearly describe the approach in detail.

In this report the relation between measurement uncertainty and the warranty 'band' is discussed; a reduction in uncertainty would mean a better warranty condition. Therefore, it is definitely worthwhile to reduce the installation uncertainty component by standardizing the procedure, i.e. incorporating the drilling of holes for the iSpin sensors in the manufacturing process of the turbines.

In ECN's view the most critical aspect of the iSpin Guardian approach is the NTF stability in wake conditions. In ROMO Wind's ideal situation this aspect is covered in an IEC standard such as IEC 61400-12-2. It is acknowledged that the development of such standards is a very time consuming process, which might not meet the business needs of ROMO Wind. Alternatively, NTF stability in wake conditions might be covered in internationally

acknowledged recommended practices and/or guidelines as for instance in the framework of IEA Wind or MEASNET. The lowest level of coverage might be a mutual agreement between the turbine manufacturer and the wind farm owner, but this is not advisable. In any case international and industry acceptance of particularly the aspect of NTF stability in wake conditions is necessary for ROMO Wind and in order to achieve this, more evidence is required. Various independent studies should demonstrate under which conditions the NTF is stable, and preferably why. ECN acknowledges that the cases presented so far are very promising.

Particularly, ECN advises ROMO Wind to demonstrate for instance that the NTFs obtained under various wake conditions, i.e. partial wake, near wake, far wake and multiple wake, are not only equal to each other, but also the same as the one obtained according to IEC 61400-12-2. Here, the case of partial wake is of particular interest as the wake might hit the rotor, affecting the turbine's power, but not the sensors. Means to assess these aspects are for instance sector-wise NTF and a shorter averaging time to cope with the wake dynamics. In addition, the general aspect of complex fields in relation to NTF could be examined more closely using detailed modelling such as CFD or LES.

ROMO Wind was recently awarded an EUDP grant from the Danish government. At least 90 turbines will be equipped with wind tunnel calibrated iSpin anemometers and tested for a whole year. This project is an ideal opportunity for ROMO Wind to tackle the identified steps ahead.

ECN advises ROMO Wind to demonstrate that the NTFs obtained under the various conditions are the same.

ROMO Wind was awarded an EUDP grant to tackle the steps ahead.

### 3.3 Prospects

The iSpin Guardian approach is meant as a wind farm performance monitoring approach to be adopted in warranty contracts. Of course the installation of the iSpin sensors on the turbines in a wind farm has additional advantages outside the scope of the iSpin Guardian approach. ROMO Wind has already convincingly demonstrated the capabilities of iSpin to detect yaw error. Therefore, the use of the iSpin Guardian approach automatically enables operators to correct for potential yaw errors and perhaps other improved operation and maintenance, depending on the contracting party to do this. These are considered as quick wins for the wind farm owner.

In the current set-up of the iSpin Guardian approach, every wind farm is equipped with a meteorological mast. For one turbine the NTF is determined and is applied for all turbines in the wind farm assuming the terrain does not have significantly different complexity properties within the wind farm. ROMO Wind has shown cases to ECN where the NTF was obtained in one terrain and applied on a turbine in a very different wind farm with very different terrain complexity. The obtained NTF was shown to be similar to the manufacturer's power curve. This addresses the aspect of stability of the NTF for a specific turbine type over various terrains. The potential of this aspect is that the NTF needs to be determined only once and can be applied to all wind turbines in all terrains without the necessity to erect a meteorological mast in the wind farm. It is acknowledged that the aspect of NTF stability for various terrains is very similar to the aspect of the NTF stability in wake conditions. Again, sufficient independent verification and demonstration is necessary for ROMO Wind to get this aspect internationally and industry accepted.

The last prospect of the iSpin Guardian approach discussed in this section is the opportunity to consider relative power curves. In the current set-up, the NTF is the bridge between what the iSpin measures itself and the free stream wind condition using the meteorolog-

ical mast and setting the absolute value of the (nacelle) power curve. If the goal is to produce relative power curves, the potential advantage is that the step of determining the NTF and related uncertainties can be omitted. In ECN's view a disadvantage would be to value the relative differences: differences (whether expressed in MWh or %) may have different meanings from one situation to the other. Therefore, in order to adopt this approach ECN advises to clearly describe and demonstrate this approach. For now, it is identified as a prospect.

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