Final report

1. Project details

Project title	Large Spinner Anemometer Performance Demonstration Project
File no.	64016-0059
Name of the funding scheme	Energy Technology Development and Demonstration Program
Project managing company / institution	ROMO Wind A/S
CVR number (central business register)	33964811
Project partners	DTU Wind Energy
Submission date	12 September 2021

2. Summary

Accurate, precise and transparent measurements of "free wind conditions" are critical to the wind industry. To achieve highest accuracy and precision, the "free wind conditions" are usually measured by reference systems such as me masts or remote sensing devices (RSD) at a distance of 2-4 diameters from the wind turbine (see IEC 61400-12-1:2017). Alternatively, measurements at the nacelle behind the rotor or at the spinner in front of the rotor can be used (see IEC 61400-12-2:2013). For these measurements, a transfer function is needed that maps the local wind conditions to the "free wind speed".

The Performance Transparency Project (PTP) was established to demonstrate on a broad scale that a spinner transfer function (STF), once established for a turbine type, can be applied at different times of the year and in different complex terrain. Time and terrain dependent STF robustness was evaluated by independent 3rd parties and DTU Wind Energy for 3 different turbine types at 8 wind farms in different terrains.

Summarized findings are:

- STFs generated for a turbine type are in fair agreement with each other
- STFs are pre-dominantly sensitive towards turbulence intensity (TI)
- STF should be created in flat terrain
- STF being generated in flat terrain can be applied in all other terrains
- STF transfer uncertainty (both time wise and terrain wise) is ~2% of "free wind speed".

Based on the PTP it was possible to create a revised version of a best practice for using iSpin spinner anemometer as well as recommendations to re-work the IEC 61400-12-2 standard. With the results of the PTP, the uncertainty related to intra- and inter turbine STF transfer was systematically assessed using large scale field measurements. This allowed to close the gap between the calibration of the STF and the application of the STF on multiple wind turbines. The best practice therefore provides now a complete uniform methodology of measurement, analysis, and reporting of wind measurements utilizing spinner anemometry.

3. Project objectives

3.1 Objectives of the project

Accurate, precise, and transparent measurements of "free wind conditions" are critical to the wind industry. The need and application of these measurements ranges from power curve verification and performance monitoring to remaining useful lifetime estimation, curtailment management optimization, bat protection control and as a basis for calculation of compensation payments in case of grid management.

To achieve highest accuracy and precision, the "free wind conditions" are usually measured by reference systems such as met masts or remote sensing devices (RSD) at a distance of 2-4 diameters from the wind turbine (see IEC 61400-12-1:2017 [C2]). Alternatively, measurements at the nacelle behind the rotor or at the spinner in front of the rotor can be used (see IEC 61400-12-2:2013 [C1]). For these measurements at the turbine position, a transfer function (either a nacelle transfer function or a spinner transfer function) is needed that maps the local wind conditions to the "free wind speed", i.e., the wind speed without the rotor induction caused by the turbine itself.

The Large Spinner Anemometer Performance Demonstration Project in the following report titled as Performance Transparency Project (PTP) was established to demonstrate on a broad scale that a spinner transfer function (STF), once established for a turbine type using iSpin measurement at the spinner, can be applied at different times of the year and in different complex terrain. A successful demonstration would allow users of the iSpin spinner anemometer technology to obtain accurate and precise wind data without the need for a met mast or RSD - not only for specific wind turbines, but for all turbines of their choice.

To achieve this demonstration, time and terrain dependent STF robustness was evaluated by independent third parties and DTU Wind Energy for 3 different turbine types at 8 wind farms in different terrains (flat, semi-complex, complex and offshore). Between 7 and 22 months of combined iSpin, SCADA, and reference system data was collected and evaluated for each wind farm with the following objectives:

- What is the time wise robustness of the STF?

  This is important for the intra-turbine STF transfer., i.e.: generation of STF during one period and application in another period at the same turbine

- What terrain wise robustness of the STF?

  This is important for inter-turbine STF transfer, i.e.: generation of STF in one terrain for a specific turbine type and application in another terrain at the same turbine type

The knowledge about the combined time and terrain wise robustness allows the flexible application of the STF independent of terrain and time.

To familiarize 3rd party consultants - accredited for power curve verification according to IEC 61400-12-1 and -12-2) - with the iSpin technology and its capabilities was another positive side effect of the PTP. To each of the selected 3rd party consultants one turbine type was assigned to evaluate the STF robustness. The review of the PTP data led to suggestions by the 3rd party consultants to improve the procedure around calibration and application of iSpin spinner anemometry for power curve verification according to IEC 61400-12-2.

The found results concerning the STF robustness have been used to create a revised best practice method for using iSpin spinner anemometry. The purpose of the spinner anemometry best practice report is to provide a uniform methodology of measurement, analysis, and reporting of wind measurements utilizing spinner anemometry. With the results of the PTP, the uncertainty related to intra- and inter turbine STF transfer was systematically assessed using large scale field measurements. This allowed to close the gap regarding calibration of the STF and multiple application of the STF on wind turbines, which was the key objective of the demonstration project.

Based on the revised best practice method a recommendation for re-working the IEC 61400-12-2 standard concerning components using spinner anemometry and a recommendation for re-working the IEC 61400-12-2 methods for the use of spinner anemometry was created by DTU Wind Energy. The best practice method as well as the recommendations for re-working the IEC 61400-12-2 will be made public by DTU after the end of the demonstration project. This will enable interested users to gain a detailed and deep understanding of the iSpin technology.

This demonstration project was also regarded as a method to gain further market acceptance for the iSpin technology. Due to changing market requirements and supported by the findings and continued dissemination of the demonstration project, the focus of the iSpin application has shifted from initial yaw fault detection to a much broader range of applications. Depending on the customer needs iSpin is used e.g., for independent and transparent power curve evaluations, performance change detections, turbulence intensity evaluations and providing wind speed data (see Figure 1).

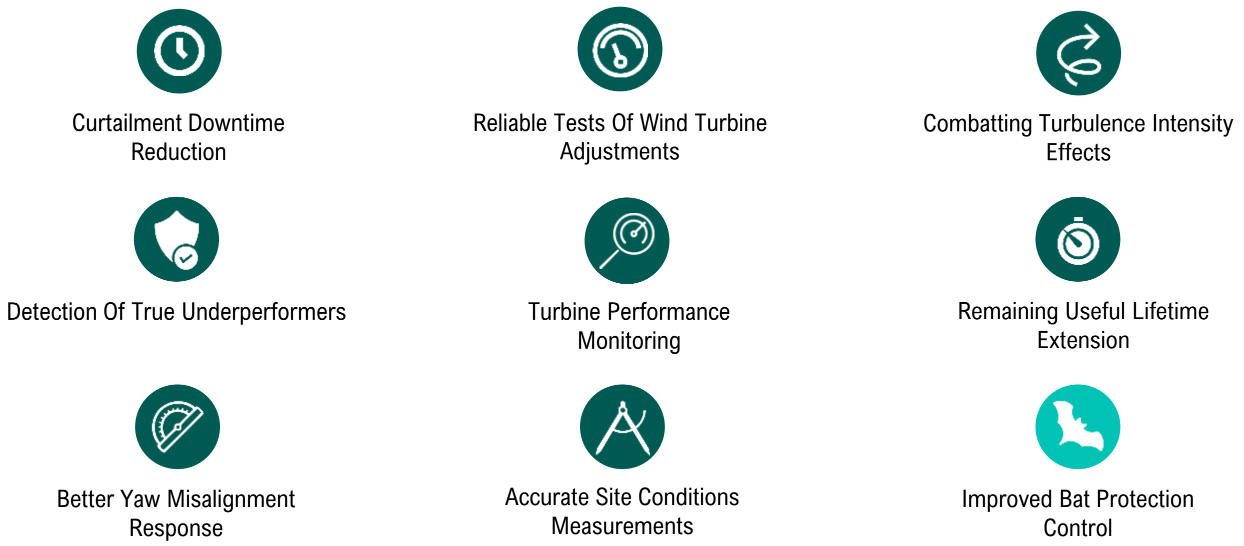


Figure 1: Current iSpin application areas

The PTP also resulted in a very large data base containing combined iSpin, SCADA and reference data for different turbine types and sites. During the PTP some part of the combined data was already used by individual project participants (e.g., to evaluate performance changes after applying different control schemes) and for a master thesis supervised by DTU Wind Energy. Furthermore, it is planned that anonymized data can be shared with interested universities or institutes.

3.2 Energy technology which has been demonstrated

A spinner anemometer is a wind measurement instrument integrated with the spinner of a wind turbine. A spinner anemometer utilises the aerodynamic flow over the spinner surface to determine the wind speed and wind direction at the position of the spinner. Three one-dimensional sonic sensors, mounted at equal azimuthal separation on the spinner, measure directional flow speeds over the surface of the spinner. With these flow speed measurements and a measurement of the rotor azimuth position (based on accelerometer measurements at the foot of each sonic sensor) a conversion algorithm converts the measurements to a wind vector, i.e., a representation of the horizontal wind speed U_{hor} at the rotor centre, a yaw misalignment angle γ and a flow inclination angle β [C4].

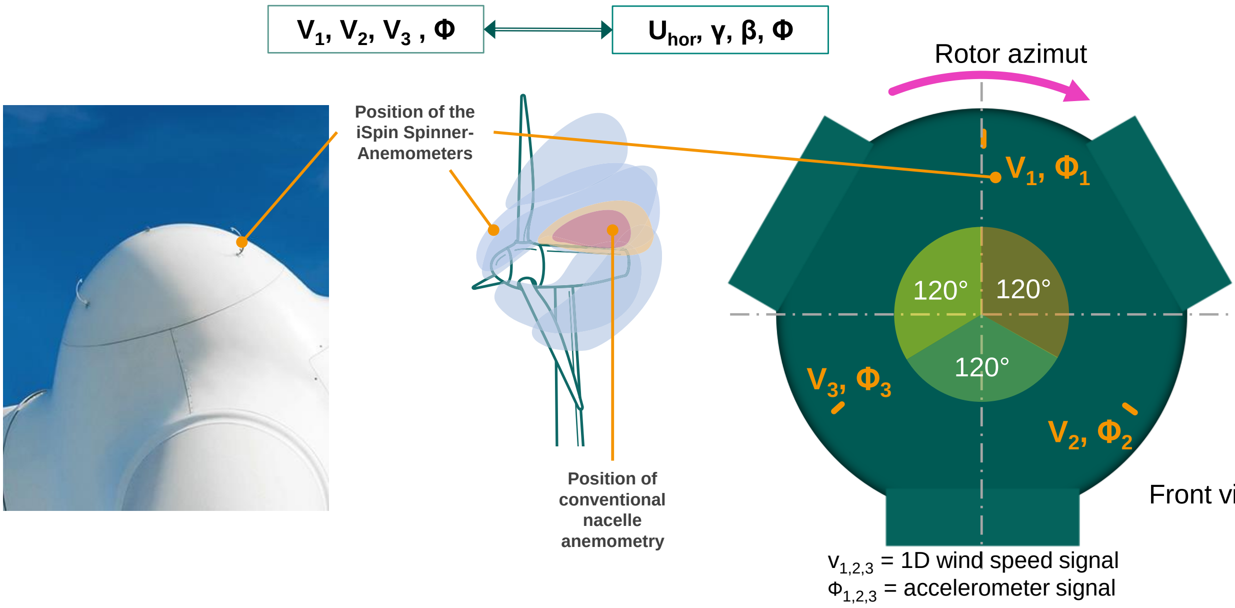


Figure 2: iSpin Technology - Basic measurement principle

Figure 3: iSpin 4 controller and iSpin 4 sensor

The philosophy of a classic power curve is to measure the “free wind speed” at the rotor centre as if the wind turbine was not there (i.e., it is free of turbine rotor induction). This definition of the measured “free wind speed” requires to take into account and corrected for: the influences on the spinner anemometer measurements from induction due to the blades; and the influence from the spinner, the nacelle and the blade roots. The influence of induction due to the blade loads is taken care of by what we call the Spinner Transfer Function (STF), which is very similar to the Nacelle Transfer Function (NTF) for nacelle-mounted anemometry defined in the

IEC61400-12-2 standard [C1]. The influence due to the flow over the spinner, and the induced wind speeds due to the nacelle and blade roots are taken care of by the spinner anemometer algorithm, which converts the local directional wind speeds on the spinner surface and the rotor azimuth position to the wind conditions at the rotor centre. The horizontal wind speed at the rotor centre is transformed into "free wind speed" by applying a STF [B15].

4. Project implementation

4.1 Project evolvement

The Performance Transparency Project (PTP) was a collaboration between Romo Wind A/S (Denmark) and DTU Wind Energy (Denmark) as scientific partner. The detailed evaluation of the sites was assigned to experienced 3rd party consultants, accredited for power curve verification according to IEC 61400-12-1 Ed1 and Ed2 as well as IEC 61400-12-2 Ed1.

In total, 8 wind farms covering 3 turbine types and 4 different terrain types have been evaluated. Except for the Spinner Transfer Function of turbine type C all other turbine types (A and B) have been evaluated for 3 different terrain types.

Depending on the specific sites up to 22 months of combined iSpin, SCADA and reference system data (from met mast or nacelle lidar) were available and have been used for evaluation.

Table 1: Overview of evaluated turbine types and sites

Turbine Type	Country	Terrain	3rd party	Combined meas. duration in months	# of iSpins	Reference System
Vestas V112	Romania	Flat	DNV-GL	14	10	Met mast
Vestas V112	Belgium	Offshore	DNV-GL	16	10	Nacelle Lidar
Vestas V112	Croatia	Complex	DNV-GL	22	10	Met mast
Enercon E82	Poland	Flat	DWG	15	10	Met mast
Enercon E82	Portugal	Semi-complex	DWG	19	9	Met mast
Enercon E82	Portugal	Complex	DWG	16	10	Met mast
Vestas V90	France	Flat	UL International	12	8	Met mast
Vestas V90	Portugal	Complex	UL International	7	10	Met mast

4.2 Risks and unexpected problems during project execution

A large field measurement campaign project contains in itself several risks to fail or be delayed. Table 2 lists the main technological risks which occurred during the PTP and how they have been handled.

Table 2: Technological risks during the demonstration project

Technological risk	Impact on the project	Dealing with risk
Wind turbines of same type are operated significantly different in different wind farms.	Evaluation of Spinner Transfer Function (STF) transferability becomes significantly more difficult and less conclusive	Approach participants (wind farm operators) to force Original Equipment Manufacturer (OEM) to parametrize PTP wind turbines equally. (Successfully done)
Reference systems (met mast or LiDAR) or iSpin systems do not work properly.	Delayed calibration process and long term (seasonal) evaluation of STF	Daily/weekly check of reference system status; spare systems (wind tunnel calibrated sensors).
Variations between the iSpin-STFs cannot be clearly assigned to a cause	Higher constraints in the iSpin STF application than initially anticipated or higher uncertainties to be assigned to intra and inter wind farm application of iSpin STF	Define feasible application constraints; Focus on identifying/isolating drivers (environmental quantities) responsible for STF sensitivity.

Besides technological risk unexpected problems or obstacles can occur during the project execution. For this demonstration project these unexpected problems mainly caused delays in the project finalization and were handled by applying for a time wise project extension. Unexpected problems were:

- Difficulties to identification of suitable turbine type C sites (sites fulfilling the requirements for PTP). To solve this an extensive screening based on global wind turbine data base was performed and research entities have been contacted. Finally, two sites with met mast have been identified and iSpin was installed for combined measurements in 2019.
- Unforeseen issues in the re-location/refurbishment of met masts (due to building permission procedure, logistics related to sensors) or installation of nacelle-based LiDAR (due to offshore weather condition) as reference wind measurement system for Spinner Transfer Function generation and evaluation at turbine type A and B sites (V112 flat terrain, V112 Offshore; E82 flat terrain). Finally, the reference wind measurements systems were made working in 2019.
- Significant delay to reset optimized turbine parametrization of V112s in flat terrain back to same settings as for V112s in complex terrain. This was solved with support by the participant who successfully pushed OEM to toggle for all PTP turbines in flat terrain between optimized and normal operating mode. Usable measurement period started in 2019.
- Delay in provision of SCADA and met mast data by participants. To overcome this weekly data availability checks as well as frequent meetings (TelCos) with participants have been set up. This resulted in a scheduled data provision.
- Delay in met mast refurbishment at site complex site for turbine type C (Vestas V90-3MW) caused by unavailability of terminals for measurement sensors. To solve this ROMO Wind contacted several terminal providers and finally arranged delivery of missing terminal.
- COVID-19 pandemic caused delays in 3rd party consultant evaluation for turbine type A and B and the met mast refurbishment activity in the complex site for turbine type C.

- Staff availability issues and re-structuring of 3rd party consultancy team responsible for Turbine type C evaluation caused individual and summary reports for turbine Type C (Vestas V90-3MW) not being finished until end of July 2021. To minimize the impact of the objectives of the project ROMO Wind agreed with DTU Wind Energy that instead of summary reports for turbine type C status presentations will be considered for the overall evaluation and update of the best practice method.

4.3 Project implementation

The Performance Transparency Project was divided in different work packages which are linked to each other. The general project implementation for the different work packages (including original planned and real milestone achievement in months and milestone fulfilment) can be found in Table 3.

Table 3: Project implementation with original milestone month and realised milestone month

MS	Milestone name	WPs	Plan. month	Real. month	Status & Means of verification
M1	Site and turbine type agreement	1	4	12 36*)	**Done for Turbine Type A & B** **Done for Turbine Type C**
M2	Selection of 3rd party consultants via tendering process	1	5	7	**Done** Contracts with 3rd party wind experts (DNV-GL, Deutsche WindGuard, UL/DEWI)
M3	Data base and WEB access established	2	7	8 17*)	**Done for FTP access** ***)Done for PTP web page**
M4	Measurement data for normal sites available to 3rd party experts for validation	3	13	30 34*)	**Done for Turbine Type A & B** **Done for Turbine Type C**
M5	Measurement data for semi-complex/complex sites available to 3rd party experts for validation	4	15	16 45*)	**Done for Turbine Type A & B** **Done for Turbine Type C**
M6	Measurement data for offshore sites available to 3rd party experts for validation	5	21	18	**Done (only applicable for Turbine Type A)**
M7	Conclusive robustness proof report	6	29	49	**Done (for Turbine Type A & B)**/ Final summary report for evaluated turbine types containing the proof of robustness results for normal, semi-complex/complex and offshore site.
M8	Conclusive uncertainty evaluation report	6	30	58	**Done**/ Final uncertainty components report and recommendation for re-working IEC 61400-12-2
M9	Conclusive report concerning best practice iSpin PC verification method	8	30	58	**Done/** Final best practice report

5. Project results

5.1 Reaching project objectives

To reach the original objectives systematic approaches to assess the time wise and terrain wise robustness of the iSpin STF were developed and agreed between the 3rd party consultants and DTU at the beginning of the demonstration project.

Three approaches have been used.

1. Time wise robustness evaluation approach:
   For each turbine with a reference measurement system the combined measurement data (iSpin, SCADA and reference system data) was used to evaluate variability of the STF over time. This was done by comparing STFs generated for short periods (2- or 3-months duration) with the STF generated for the entire measurement period.
   Furthermore, it was evaluated whether repeating patterns in the STF variability could be identified by comparing same seasons for two following years.
2. Terrain wise robustness evaluation approach:
   The variability of the STF over time was considered to be caused by the sensitivity of the iSpin STF function (or "free wind speed" measurement) to environmental and operational quantities (wind speed, turbulence intensity, shear, flow inclination, temperature, pressure, density, yaw misalignment, rotational speed, pitch angle) which might change over time or depending on the season. The sensitivity concerning environmental and operational quantities was evaluated by comparing the "free wind speed" measured by iSpin with the wind speed measurement of the reference measurement (met mast cup anemometer at hub height or nacelle lidar measurement) for the partial load range (wind speeds from cut-in up to below rated wind speed) and the free sector as defined by IEC 61400-12-1. A band of +/-2% around the binned ratio of 1 was agreed to be the threshold for showing no relevant sensitivity towards the evaluated environmental or operational quantity.
3. DTU applied a method called ANOVA (ANalysis Of VAriance) as another approach to evaluate the sensitivity of the iSpin STF to environmental and operational quantities. The ANOVA method was used to analyse the differences among means of the STF and aims to answer the question whether the means of different populations - e.g., STFs based on different ranges of turbulence intensity - were equal or not. The ANOVA method allowed DTU evaluating the difference in the different groups (classes) means by partitioning the total variation in the data into two components:
   - Variation of group means from the overall mean (variation between groups): $\bar{y}_j - \bar{y}$
   - Variation of observation in each group from their group mean estimates (variation within group): $\overline{y_{ij}} - \bar{y}_j$

5.2 Obtained technological results

Based on the evaluations performed by the 3rd party consultants and DTU Wind Energy the results and conclusions of the STF robustness evaluation can be summarized as follows:

- STFs generated for a turbine type are in fair agreement with each other (Difference within +/-2%)
- STF transfer uncertainty (both time wise and terrain wise) is ~2% of "free wind speed". This has been identified via the three approaches described in chapter 5.1
- STF should be created in flat terrain
- STF being generated in flat terrain can be applied in all other terrains

- STF is insensitive to topography (slope)
- No RIX limitation must be considered when applying STFs generated in flat terrain
- STFs are pre-dominantly sensitive towards turbulence intensity (accounted for by applying the 2% transfer uncertainty mentioned above)
- STFs have no additional uncertainties due to Temperature, Pressure, Flow inclination, Daytime, Season, YMA[1]

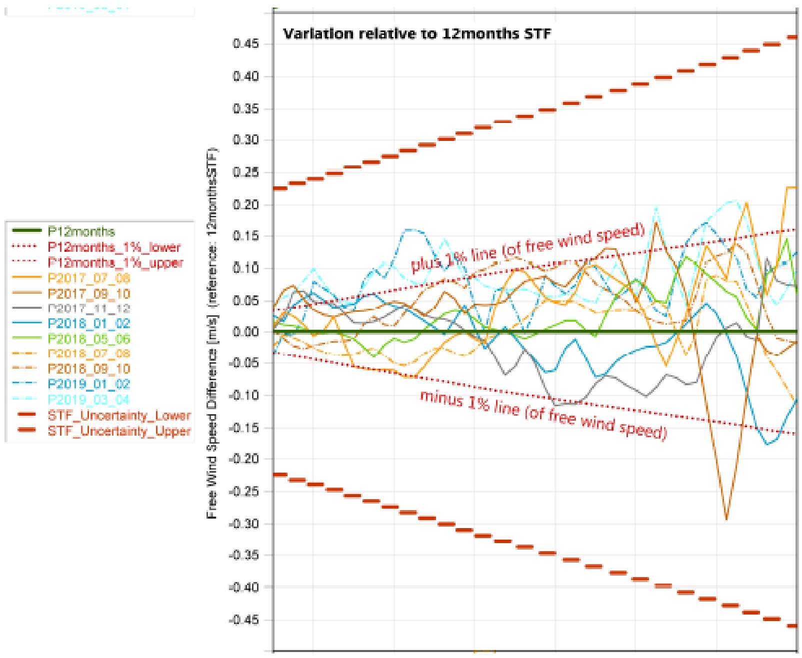


Figure 4: Time wise robustness of STF for Turbine Type A, Complex Terrain [C10]

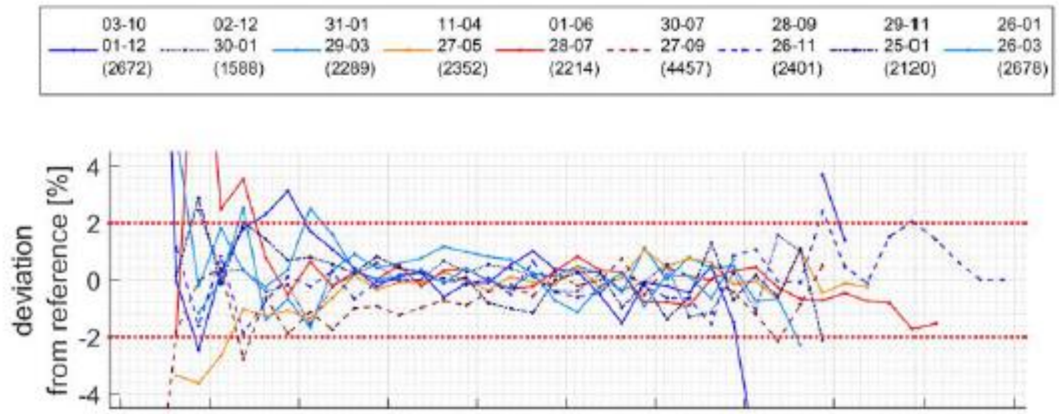


Figure 5: Time wise robustness of STF for Turbine Type B, Semi-Complex Terrain [C12]

[1] Uncertainty for yaw misalignment was considered to be 0 when during STF generation and application 10-minute average of yaw misalignment is with +/- 10°

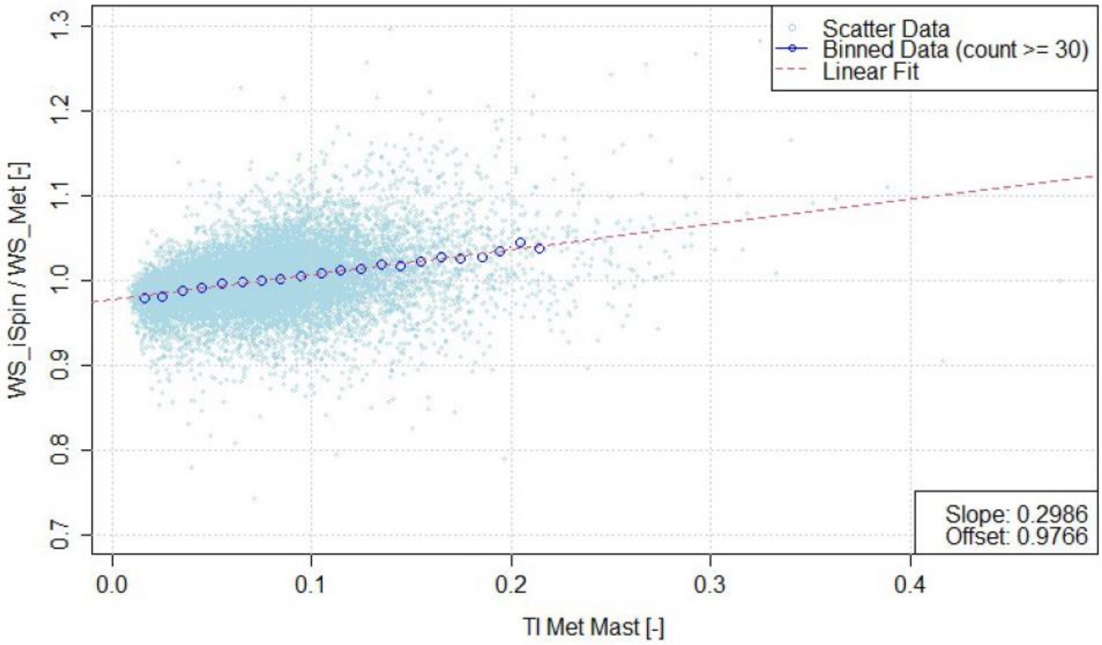


Figure 6: STF sensitivity with regard to Turbulence Intensity for Turbine Type C, Flat Terrain [C13]

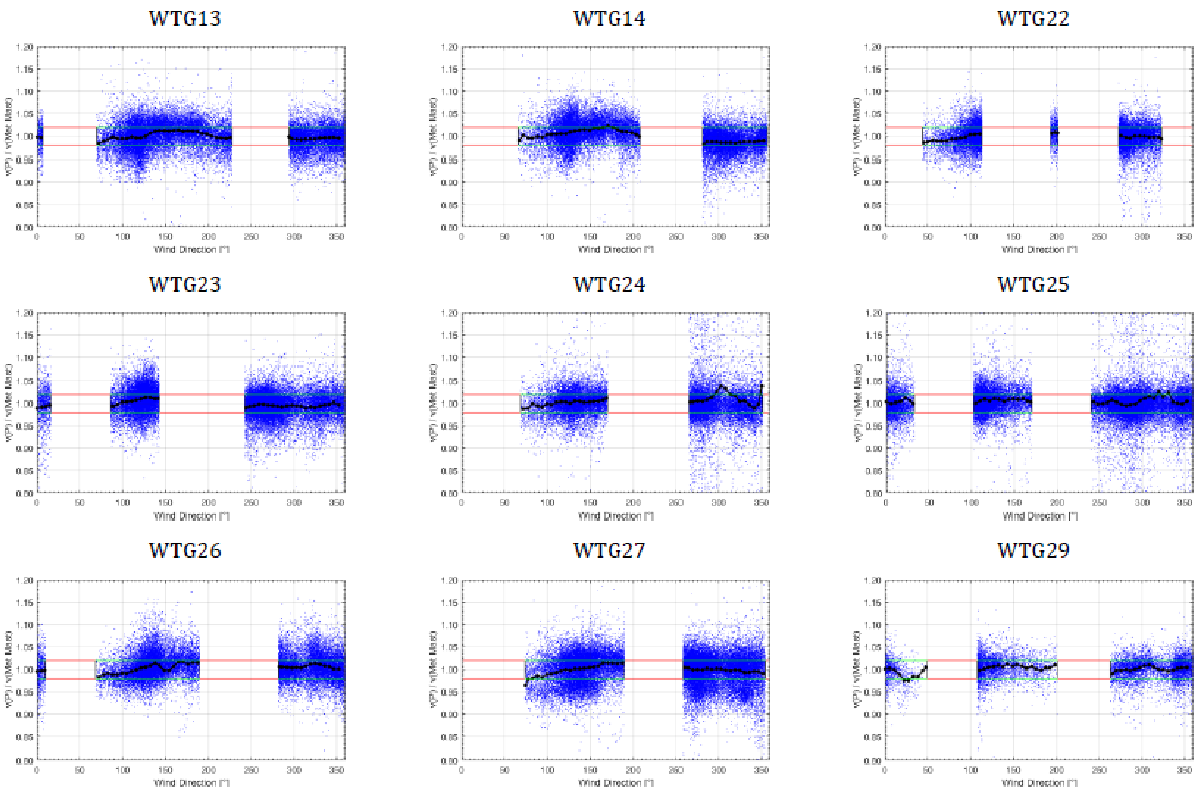


Figure 7: Self-consistency check for SPC without wake sectors (Turbine type B, complex terrain) [C11]

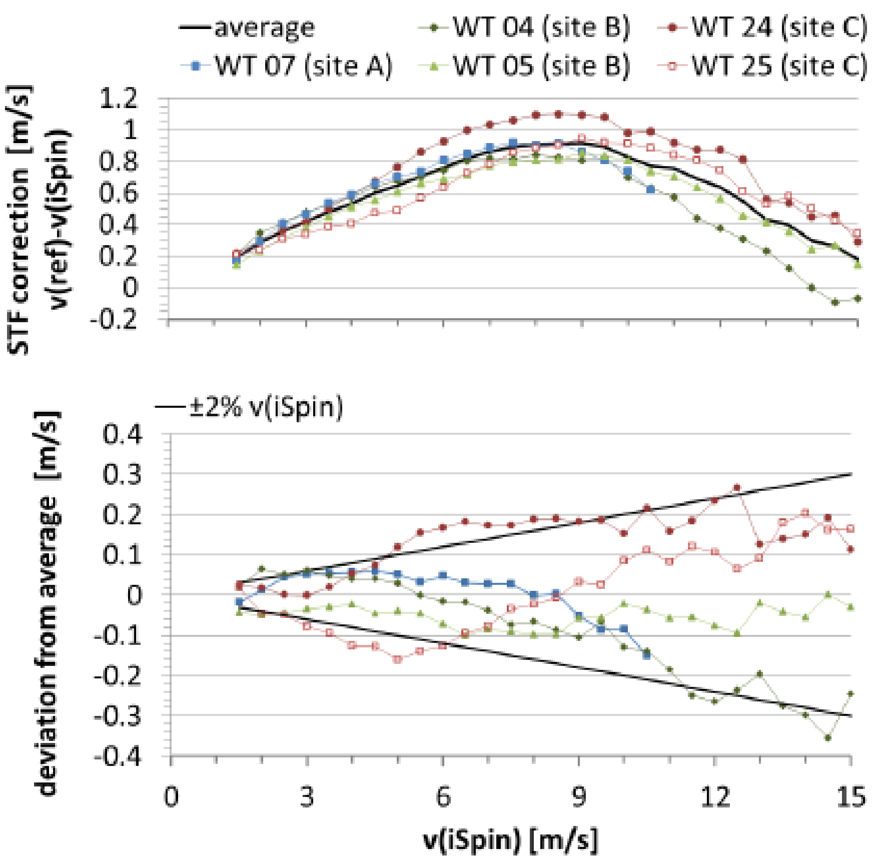


Figure 8: Comparison of STFs of Turbine Type B at different wind turbines in flat terrain (site A), semi-complex-terrain (site B) and complex terrain (Site C) [B8]

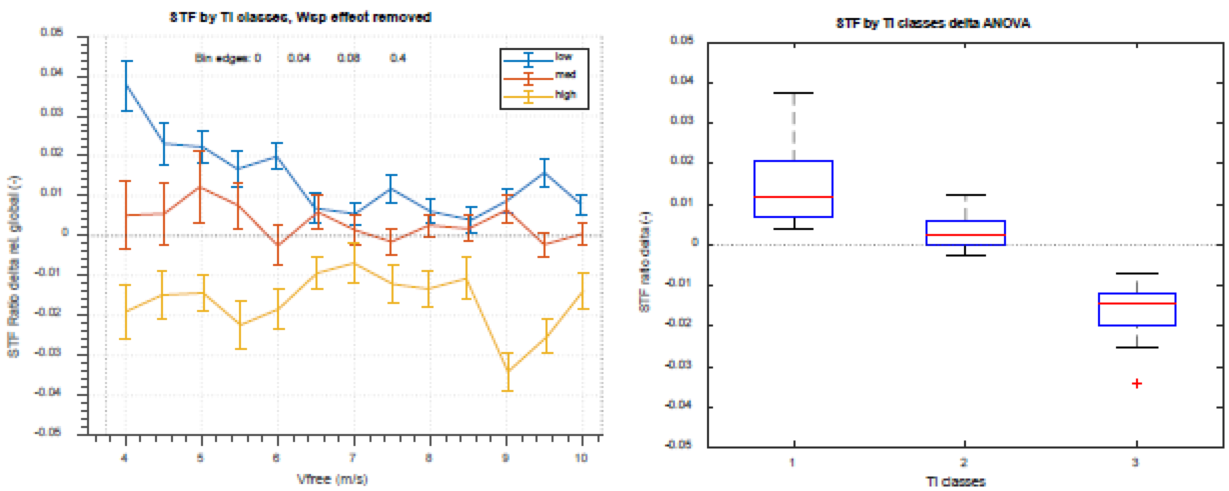


Figure 9:ANOVA results: $\Delta STF_{ratio,i,j}$ (difference vs global STF) by class of Turbulence Intensity (TI) with vertical bars being the standard error of the mean, box plot for each class [B11]

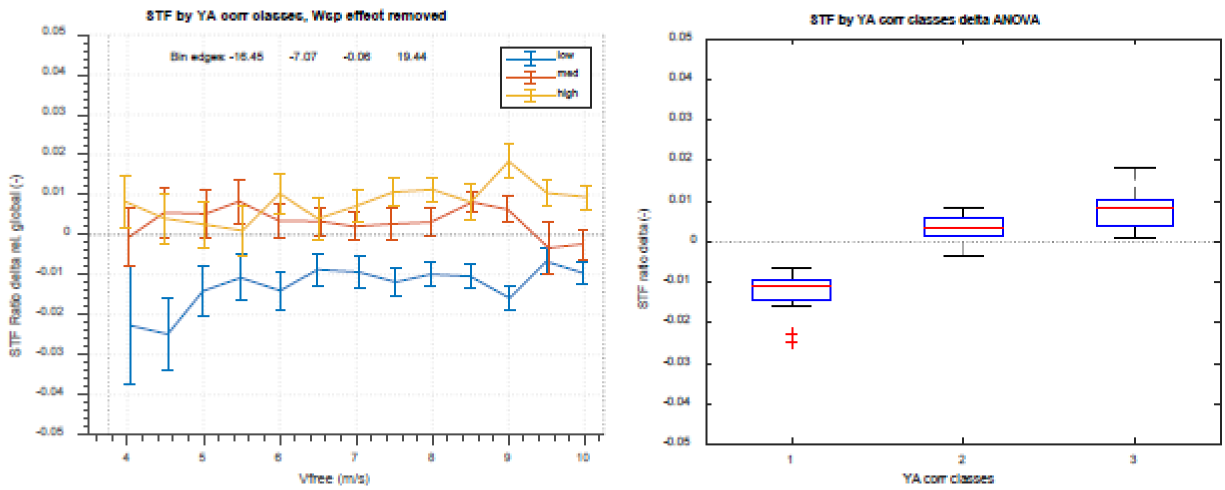


Figure 10. ANOVA results: ΔSTFratio,i,j (difference vs global STF) by class of Yaw Misalignment (YA) with vertical bars being the standard error of the mean, box plot for each class [B11]

Following work packages 7 and 8 of the demonstration project the above-mentioned findings have been converted by DTU Wind Energy into several publicly available documents. These are:

- Revised Best Practice Method for calibration and application of the STF for power performance according to the IEC 61400-12-2 standard which includes intra-turbine, inter-turbine- and inter-turbine & sites-STF-transfer uncertainty [B16].
- Recommendation to IEC for re-working IEC 61400-12-2 standard concerning uncertainty components using spinner anemometry [B17][B14]
- Recommendation for re-working IEC 61400-12-2 methods for the use of spinner anemometry [B17]

As listed in this chapter the main sensitivity of the iSpin STF towards environmental quantities was found regarding turbulence intensity (TI) with resulted in an overall uncertainty budget for the STF transfer of 2% of the “free wind speed”. The PTP data showed that the STF sensitivity towards TI seems to be low for complex sites and high for flat sites. The sensitivity towards TI was evaluated using different approaches with the aim to replace the uncertainty component by a function depending on different environmental or site-specific quantities, but a correction function led to a reduction of the STF sensitivity for each site was not found.

5.3 Obtained commercial results

Due to its nature of being a demonstration project for a measurement system the PTP did not create direct commercial results. Nevertheless, it paved the road for future business possibilities with 3rd party consultants and customer. Supported by the PTP and dissemination of PTP results ROMO Wind achieved the transition from being a yaw misalignment detection company to a problem solver and solution provider which is able to deliver transparent and independent evaluations of the turbine performance and site conditions.

5.4 Target group and added value for users

Wind measurements carried out according to the best practice procedure can be used for power performance measurements, which was the primary focus of the PTP. However, the best practice procedures as well as the lessons learned during the demonstration project can be used for a range of other purposes, for example: yaw misalignment and inflow angle measurements, measurements of “free wind speed” for wind resource verification and measurements for climatology verification related to certification, measurements of wind conditions for load validation and residual useful lifetime estimation, and measurements for control purposes on wind turbine and wind farm level. In the following section some target groups and added value for users are described briefly.

3rd party consultants

3rd party consultants being responsible for the PTP data evaluation gained deep understanding of the iSpin technology. For them and those 3rd party consultants which did not participate the PTP the revised best practice method and the recommendations to IEC will provide a detailed supplementary description on how to use iSpin spinner anemometer technology for power curve verification according to IEC 61400-12-2. This will potentially enable 3rd party consultants to offer more spinner anemometer-based power curve verifications tor customers, especially for sites were alternative verification methods like e.g., nacelle or ground based lidar measurements are not applicable or too expensive. Besides power curve verifications 3rd party consultants could also use iSpin spinner anemometer measurements for load validation purposes or more accurate and precise wind resource evaluations.

Wind turbine operators and owners

Using iSpin "free wind speed" measurements does allow operators and owners of wind turbines to monitor the performance independent from SCADA wind speed measurements (nacelle anemometry measurement under control of the OEM). This enables them to get an unfiltered and unbiased "picture" of the performance off their assets, i.e. independent from the OEMs. In case OEMs are offering hardware and software modifications to increase the power output of a turbine the precise and accurate iSpin wind condition measurements can be used as basis for a transparent, neutral, and unbiased assessment of the performance change.

By having a robust STF it becomes possible for owners and operators to request and let perform multiple power curve assessments in instead of single dedicated assessment at limited amount of reference turbines per site.

Spinner anemometer wind condition measurements like e.g., "free wind speed", turbulence intensity, yaw misalignment and flow inclination can be used to compare modelled site conditions with the real conditions at site. This approach can be for example be used to assess and optimize curtailment management obligations for already existing wind farms or for wind farms which will be equipped with more turbines.

OEMs

OEMs are offering hardware and software modifications to increase the power output for many of their turbine types. For this cases iSpin wind condition measurements can be used as basis to perform transparent, neutral and unbiased assessments of the performance change.

Universities and Institutes

During the PTP project a huge data base including long term combined iSpin, SCADA and reference system data for 3 different turbine type and for different terrain was generated. It is planned that anonymized data sets can be shared with interested universities or institutes to evaluate the iSpin measurement capabilities in more detail but also use this data for other studies.

After DTU Wind Energy has worked with the data for more than 3 years, they announced already interest for follow up studies regarding the potential of iSpin technology. Further studies might be linked to improved load analysis etc. One master thesis supervised by DTU Wind Energy concerning the ability of iSpin spinner anemometer measuring performance under wake conditions was recently finalised.

5.5 Dissemination

Dissemination of the project progress and interim results took place through various events and media and in front of the participants.

It is planned to present the final results and conclusions of the PTP in webinars organized by ROMO Wind and through other platforms or events.

A list of all performed disseminations can be found below. All referred documents can be also found on the web site created by ROMO Wind for the Performance Transparency Project: URL: http://www.ispin-ptp.com.

[A1] Windtech International, 11/16, Harald Hohlen; Article: "Performance Monitoring on all Wind Turbines at any Time"

[A2] PES Windenergy, 04/17, Harald Hohlen; Article: "Performance Transparency Project"

[A3] AWEA 2017, Anaheim (USA), 05/17, Harald Hohlen; Poster: "Holistic performance monitoring of wind farms – the iSpin Guardian approach"

[A4] PCWG meeting, Copenhagen (Denmark), 06/17, Harald Hohlen;
Presentation: "Introduction into the Performance Transparency Project (PTP)"

[A5] NRW Branchentag 2017, Düsseldorf (Germany), 06/17, Harald Hohlen;
Presentation: "iSpin-Technologie und ihre Anwendungen"

[A6] DEWEK 2017, Bremen (Germany), 10/17, Harald Hohlen; Poster: „Performance Monitoring using Spinner Anemometry"

[A7] WindEurope Workshop 2018, Vilnius, 05/18, Sowjanya Subramaniam Iyer et al.
Poster: "Performance monitoring of wind turbines using Spinner Anemometry"

[A8] Release of Performance Transparency Project (PTP) Web page, 05/18, Harald Hohlen et al., URL: http://www.ispin-ptp.com

[A9] WindEurope 2018, Hamburg (Germany), 09/18, Harald Hohlen et. al, Poster and conference proceedings: "First results from the iSpin Performance Transparency Project (PTP)"

[A10] AWEA Offshore Windpower Conference & Exhibition 2018; Karl Fatrdla et al., Poster: "A practical approach for wind park performance warranties"

[A11] WindTech 2018 conference, Porto (Portugal), 10/18, Jan Nikolaisen, Presentation: "Performance Transparency Project (PTP): Enabler for innovation & performance improvement"

[A12] Spreewindtage 2018, Linstow (Germany), 11/18, Harald Hohlen, Presentation: „Ganzheitliche Betrachtung von Windparks"

[A13] Global Offshore Wind 2019, London (UK), 06/19, Karl Fatrdla: Poster "A practical approach for Wind Farm Performance Warranties"

[A14] DTU Wind Energy, P. Gomez et al, Poster at WindEurope Offshore Conference 2019:
"Uncertainty of spinner anemometer wind speed measurements", 11/2019

[A15] EMD, H. Pedersen et al, Poster at WindEurope Offshore Conference 2019:
"Temporal Wake Modelling – Validation with iSpin Measurement", 11/2019

[A16] ROMO Wind, K. Ritter et al, Poster and Paper at WindEurope Offshore Conference 2019:
"Long term comparison of spinner anemometer and nacelle lidar data for an offshore wind", 06/2020

[A17] Spreewindtage 2019, Postdam (Germany), 11/19, Davide Trabucchi (Deutsche WindGuard),
Presentation, „Untersuchung der iSpin Messcharakteristik Leistungskurvenvermessungen"

[A18] Deutsche WindGuard, D. Trabucchi et al, Poster at WindEurope Workshop 2020:

"Sensitivity of Romo Wind Spinner Anemometer iSpin to Environmental Variables. First Experimental Results", 06/2020

[A19] ROMO Wind and DTU Wind Energy, K. Ritter, P.G. Arranz, Poster at WindEurope Workshop 2020: "Turbulence intensity comparison from lidar and spinner anemometer measurements in an offshore windfarm", 06/2020

[A20] Torque 2020 in Delft (Netherlands), 09/20, Poster and paper,
Katrin Ritter, Paula G. Arrancz, "Spinner anemometer: wind speed and Spinner Transfer Function seasonal robustness in an offshore wind farm"

[A21] International Summit on the Operational Analysis of Wind Farms 2020 in Madrid (Spain), 11/20, Webinar Presentation, Harald Hohlen, "New insights into the iSpin technology and its advanced applications"

6. Utilisation of project results

6.1 Utilization of technological results in the future

Based on the evaluations and recommendations made by the involved 3rd party consultants and DTU Wind Energy improved iSpin calibration procedures with extended quality check gates for the STF calibration have been developed by ROMO Wind. The documentation of the quality check gates increases the traceability of the iSpin spinner anemometer "free wind speed" measurement capability significantly and supports easier application of the iSpin measurement at future target sites.

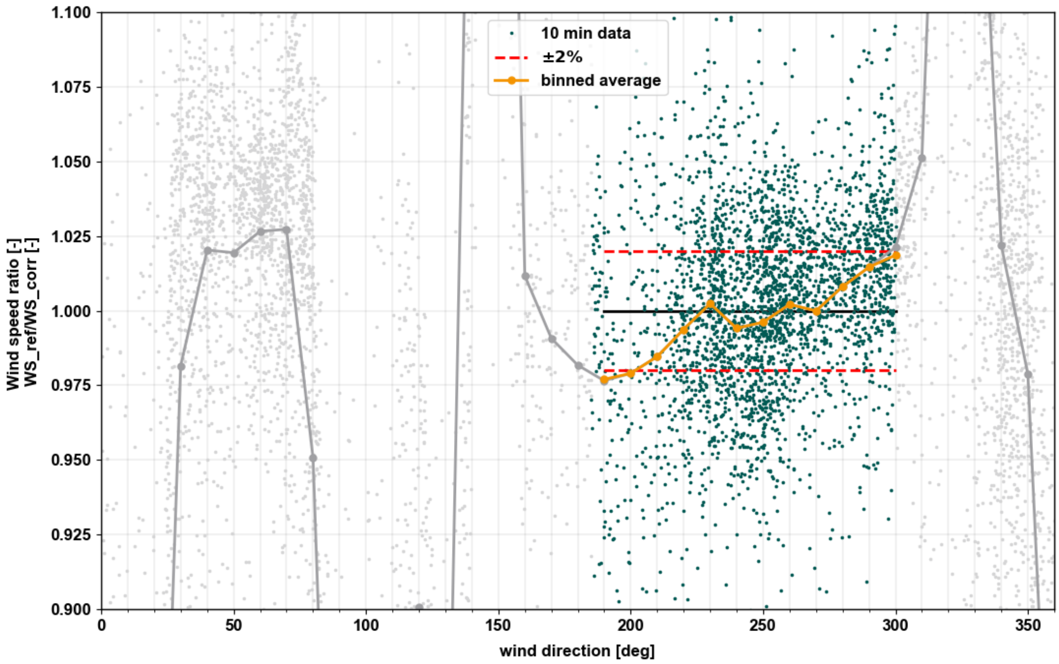


Figure 11: Directional consistency check (Wind speed ratio as function of free wind speed)

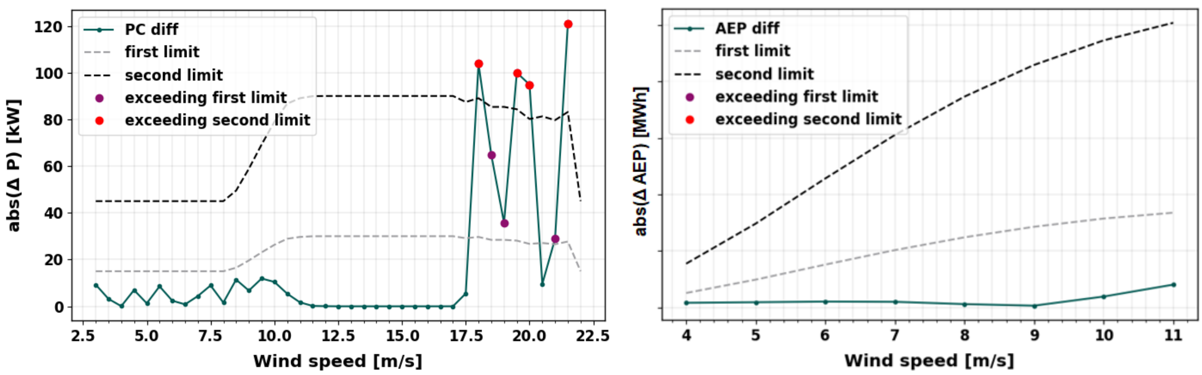


Figure 12: Self-Consistency Checks
(left: Spinner Power Curve Self-Consistency Check, right: Spinner AEP Self-Consistency Check)

6.2 Utilization of commercial results in the future

In the introduction, several applications were listed where iSpin wind measurements could be used to help customers gain better insights into their wind turbines as well as site conditions and to optimize their turbines to achieve the planned performance level.

The following figure is intended to illustrate the impact iSpin measurements could have for various aspects (applications) of improving the annual energy production (AEP) of a wind farm. The individual values are based in part on results from iSpin applications in the field.

Of growing importance will be the usage if iSpin wind condition measurement for the residual useful life estimation process. What exact impact on the overall lifetime AEP improvement is possible is depending on each site and the conditions and constraints under which the wind turbines are operating.

Some of the applications are briefly discussed in the following section.

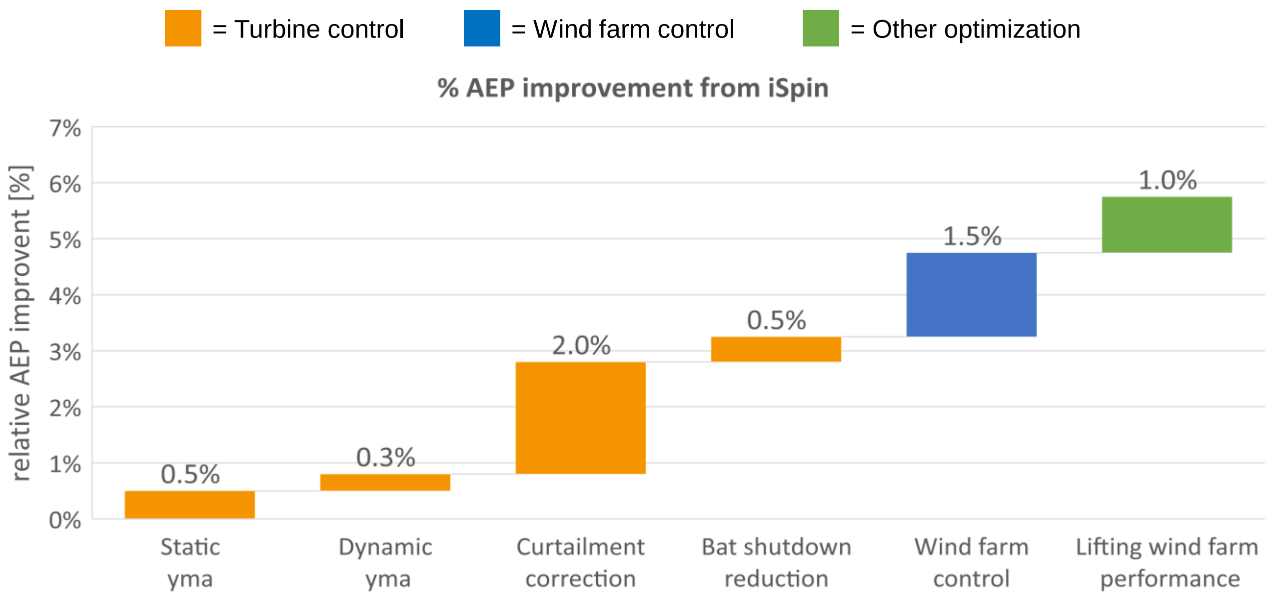


Figure 13: Illustration of relative AEP gain using iSpin for different aspects of wind turbine operation

6.2.1 iSpin for active wind farm control

Several studies show that the overall wind farm performance can be increased and the loading for wind farm turbines can be reduced if an active wind farm control scheme is implemented. According to e.g., Kanev et al [C15] the potential in AEP increasement due to active wind farm control (AWC) lies in the range of 1 to 6 %. Basically, two approaches are discussed:

1. Yaw-based AWC: By operating upstream turbines at yaw misalignment, their wakes are redirected away from the downstream turbines, letting them produce more power. Because of the yaw misalignment, yaw-based AWC could potentially increase the loads for some wind directions. Therefore, it is important to be able to evaluate the effect of AWC on the fatigue loads and even include loads into the optimization to ensure they remain lower than the nominal loads.
2. Pitch-based AWC: The axial induction of upstream turbines is reduced at below rated farm power (typically by increasing the blade pitch angle, or derating). This results in the velocity of the wake increasing, allowing downstream turbines to increase their power production. The turbulence intensity in the wake decreases as well, leading to lower fatigue loads downstream

Due to its capability to measure the wind vector hitting the turbine iSpin spinner anemometer can be applied for both approaches. With spring 2021 the Sensor Assisted Wind Farm OPeration (SAWOP) project [C17] started in which iSpin is evaluated with other remote sensing devices like ground based, nacelle and scanning lidars to figure out which combination of devices would be most suitable for an effective and efficient active wind farm control.

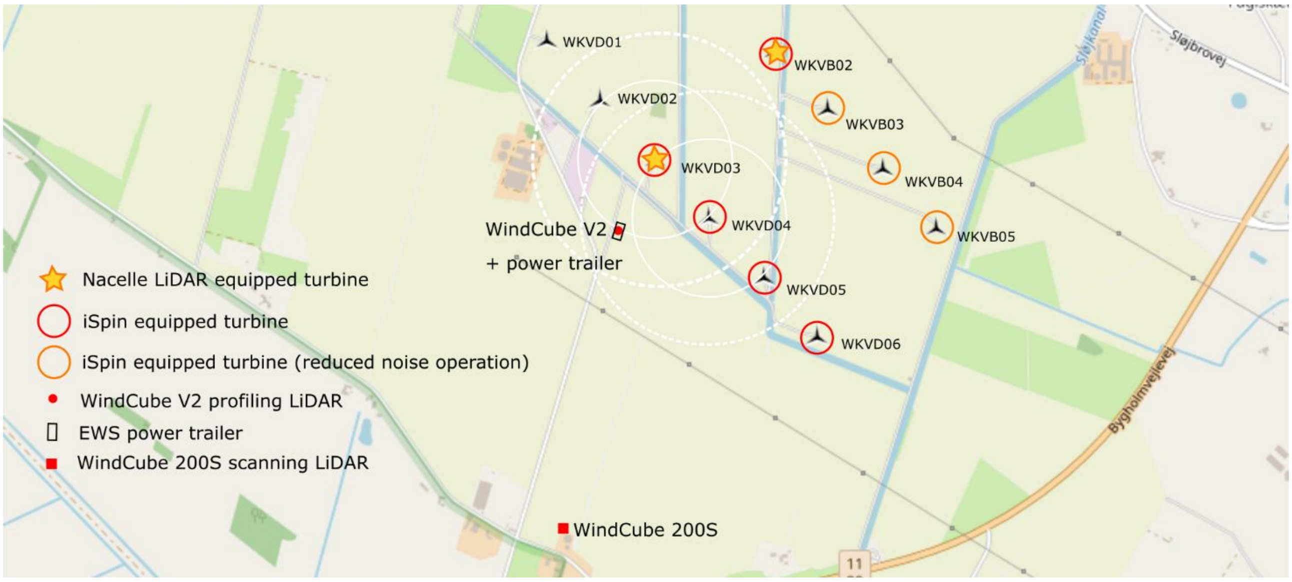


Figure 14: Measurement setup for Sensor Assisted Wind Farm OPeration (SAWOP) project [C17]

On the business development site, ROMO Wind is focussing on pursuing the yaw-based approach, because with the iSpin Yaw a system has been developed which can be used to determine and correct the actual yaw misalignment in real time (see Figure 15). This iSpin Yaw system basically allows also introducing situation dependent yaw misalignment offsets coming from the active wind farm control logic to the turbine control. An example configuration for an active wind farm control using iSpin is shown in Figure 16

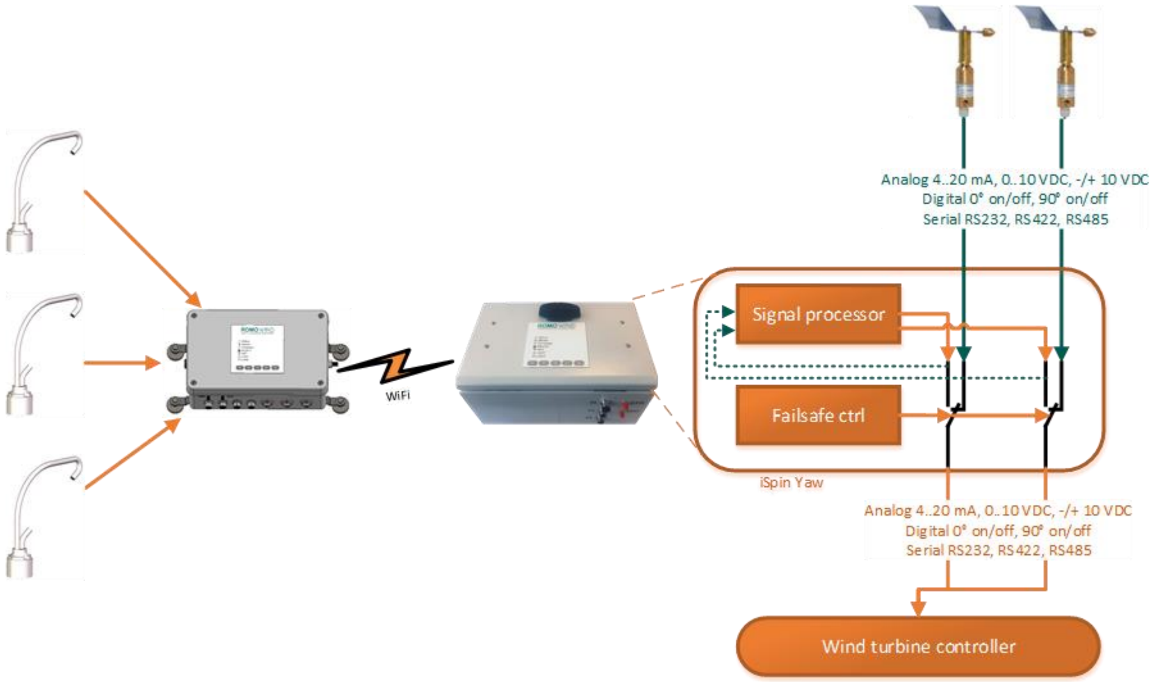


Figure 15: Principle of iSpin Yaw system

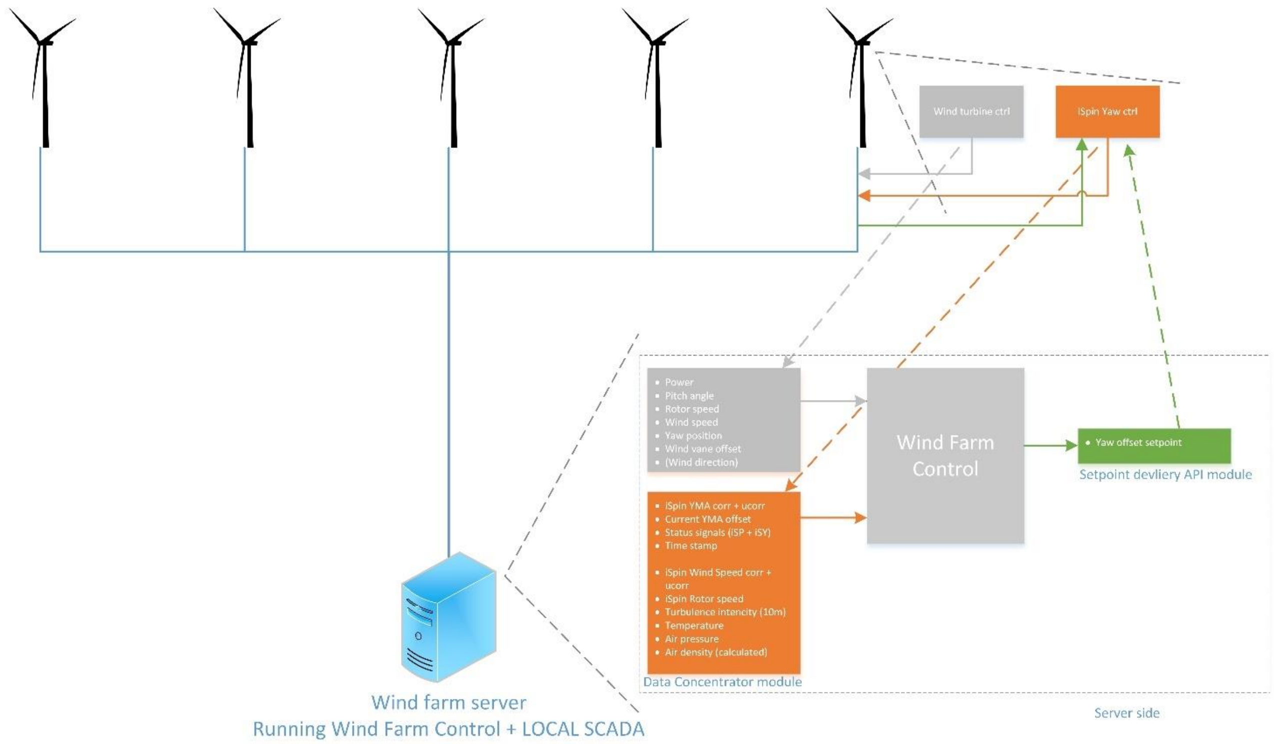


Figure 16: Example configuration for active wind control using iSpin Yaw

6.2.2 Application of iSpin in residual useful life estimation process

In addition to the aero-elastic model, wind speed and turbulence intensity are the main factors contributing to the uncertainties in estimating the remaining useful life (RUL) of a turbine. By using precise wind measurements with the iSpin spinner anemometer, the uncertainty in RUL estimation per turbine component could be reduced.

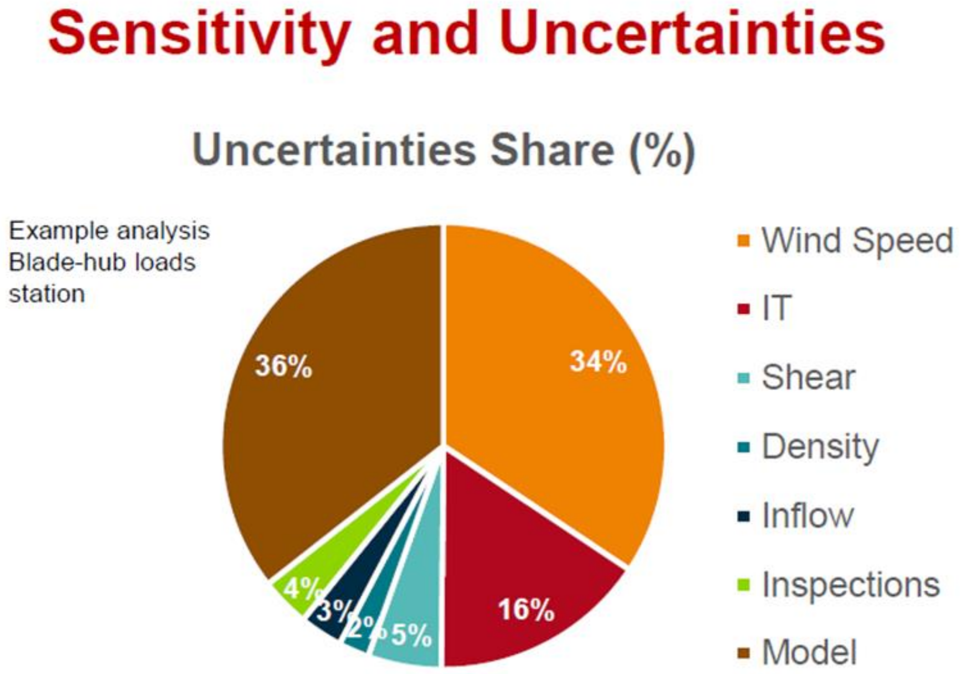


Figure 17: Wind conditions are main aspect of evaluating and managing residual useful life estimation (Source: UL International)

There will be several approaches listed in future IEC 61400-28 standard [C14] for life extension. All of them are considered valid methods for analysing fatigue accumulation over the years of wind turbines and predicting it for the future. All the analytical methods used to perform this analysis (relative, absolute, and based on load measurements) require the use of environmental data, so the relevant standard assumes that “good” wind data with a low degree of uncertainty are required to be properly evaluated in the mandatory uncertainty analysis that must be performed to follow the proposed good practices.

Life extension analyses can be considered as risk assessments with the aim of providing valuable information to wind farm operators to decide whether or not the operation of wind turbines in their present condition in the future is safe from a structural point of view, so that no unexpected failures will occur due to fatigue in the structural components.

Even if the absolute analysis is to be performed in the life extension analysis, the whole process of a relative analysis with the previously described inputs is mandatory. The uncertainties associated with the loads that will later be used in a finite element analysis remain the same in this methodology, so it is even more important to use the lowest possible uncertainty in the wind parameters, especially those that affect a higher level, such as the wind speed, Weibull distribution and turbulence intensity.

In all the analyses proposed in the upcoming IEC 61400-28, wind data (mainly wind speed and turbulence intensity) are key factors that will strongly influence the results and thus the risk assessment. Other parameters such as yaw offset, which is closely related to iSpin outputs, are also important. Currently, the most common life extension analysis performed by the various operators is the relative analysis, which is based on a comparison between the fatigue limits met under the wind turbine certification conditions (various IEC classes such as IA, IIB, etc.) and the site-specific conditions of the individual wind turbines. Following steps are needed for this type of analysis:

Set-up of an aeroelastic model:

A physical-mathematical representation of the wind turbine needs to be established that replicates (clones) the performance of the real wind turbine in terms of operation properties (electrical power, rotor speed, pitch angle…) and loads in all the various components

Analysis of the operating conditions:

Yaw misalignment, availability, transient events, curtailments, and all relevant operating parameters must be accurately recorded in order to best emulate the wind turbine's past and thus predict how fatigue has accumulated. Here, analysing the past is also a good way to predict what can be accomplished in the future, although proper monitoring of turbines is recommended.

Analysis of wind conditions:

Air density, inflow angle, wind shear and mainly, Weibull distribution and turbulence intensity are key factors that strongly affect the loads results of the site-specific loading. Again, analysing the past is also a good way to predict what can be accomplished in the future, although proper monitoring of the wind conditions is recommended.

For both operational and wind analysis, adequate monitoring with precise, accurate and independent iSpin data over the lifetime of the turbine is possible and beneficial. Therefore, the next step is to integrate the iSpin data of yaw offset, wind speed and turbulence intensity into a hybrid 24/7 online data analysis tool. This tool will enable measurement of wind turbine and wind turbine component lifetime and provide comprehensive active asset management.

6.2.3 Application of iSpin for curtailment management re-assessment and in repowering of wind farms

The ability of iSpin to measure accurate and precise wind conditions such as wind speed and turbulence intensity (TI) enables to check existing curtailment obligations (resulting from structural stability calculations based on wind and turbulence models) against real measurements performed at the affected turbines.

In 2019 iSpin was successfully used to demonstrate that the wind sector management based on model calculations was too conservative for two turbines located very close to each other (see Figure 18). 12-months of TI measurement in combination with wind speed and wind direction measurements were used to determine the actual curtailment needs, resulting in curtailment obligations being removed in 2020. After another 12-months iSpin measurement period, during which both turbines operating without curtailment, it was confirmed that no significant exceedance of the design turbulence intensity distribution was visible for either neighbouring turbine (see Figure 19).

The same approach to verify the need of curtailment obligations can be also applied if a partial repowering of existing wind farms or the addition of new wind turbines to an existing wind farm is planned. Here iSpin can be used to record the wind conditions of the existing wind turbines before the new turbines are installed. The results of these measurements can be compared with the measurements obtained after installation of the additional turbines and used to fine-tune curtailment obligations based on previous model-based simulations.

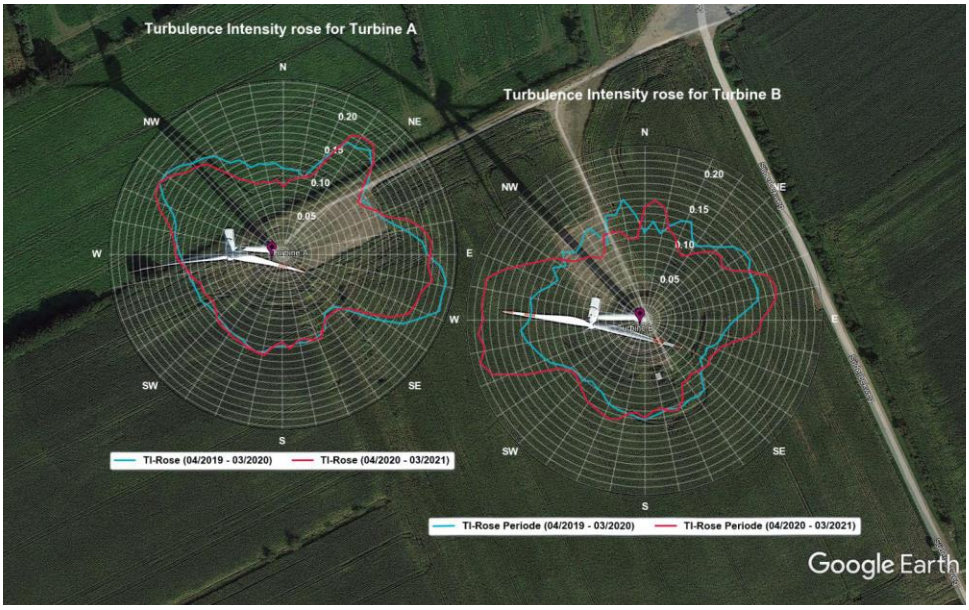


Figure 18: Park layout and turbulence intensity (with and without curtailment)

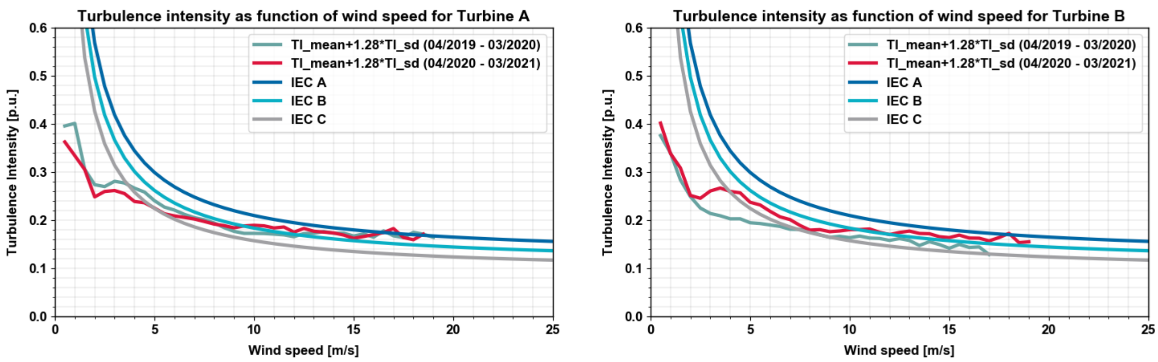


Figure 19: Turbulence intensity comparison for two neighboring turbines (with and without curtailment)

6.2.4 Bat protection control using iSpin data

While being considered a sustainable energy source, wind turbines have an impact on their environment, especially on airborne animals. Bats have a mortality risk from the direct collision with the rotating blades and from the so-called barotrauma, while being protected under EU law and many species being considered as endangered. To mitigate these risks, it is an often-seen approach in European states to tie building permissions of wind projects with condition limits (combined with air temperature limits), under which the turbines must shut down, because these conditions indicate high bat activities.

In case of idling or stop cases turbines with large chord length at the blade root area tend to measure with the conventional nacelle significantly lower wind speeds than actually arriving at the turbine. This is caused by the installation of the nacelle anemometry behind the rotor, i.e. for slow rotational speeds or turbine standing still the rotor blade section blocks the wind. This disadvantage can be avoided by using spinner anemometer measurements as input for the bat protection systems. Figure 20 shows the wind speed ratio and the difference between SCADA wind speed (y-axis) and the iSpin wind (x-axis). For shut down iSpin measures significantly higher wind speeds compared to the nacelle anemometry. The impact of this difference on AEP improvement potential due to using iSpin for bat protection control can be seen in Figure 21.

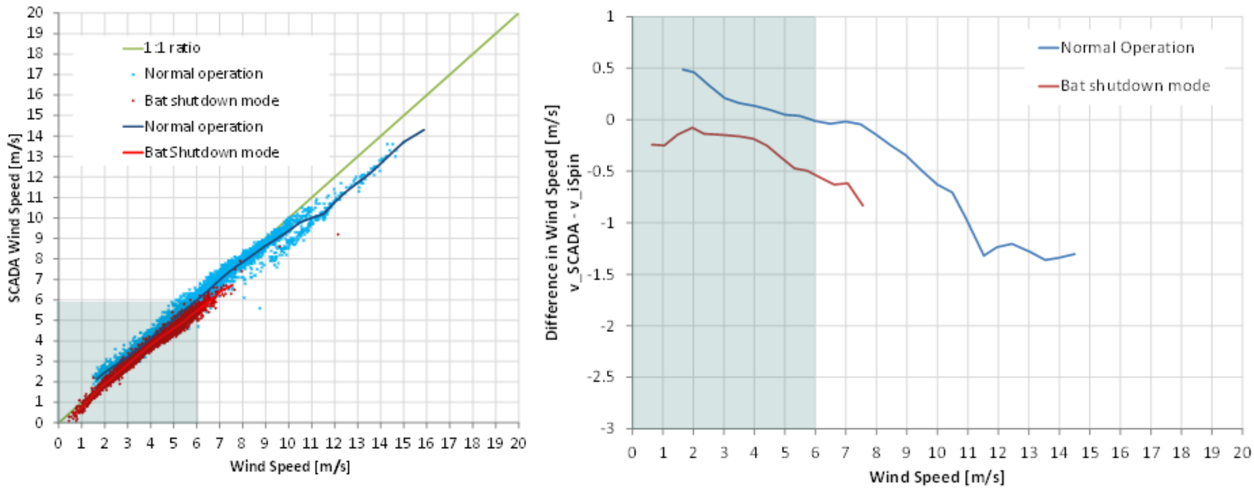
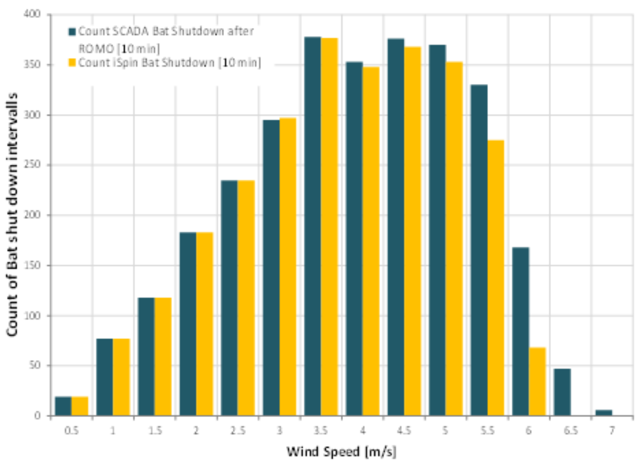


Figure 20: Differences between iSpin and SCADA "Free Wind speed" measurements



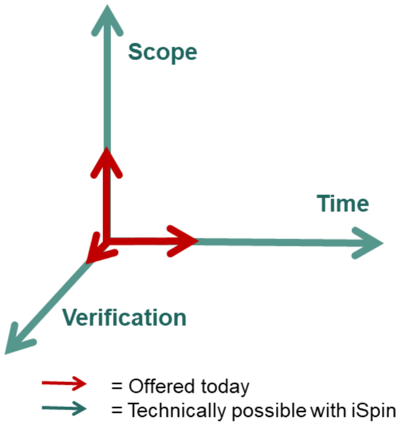
Wind BIN	Count iSpin Bat Shutdown [10 min]	Count SCADA Bat Shutdown [10 min]	Difference iSpin – SCADA [h]	Difference iSpin - SCADA [kWh]
0,5	19	19	0,00	0,00
1	58	58	0,00	0,00
1,5	107	107	0,00	0,00
2	143	143	0,00	0,00
2,5	197	197	0,00	0,00
3	250	250	0,00	0,00
3,5	296	300	0,67	68,00
4	274	283	1,50	232,50
4,5	315	326	1,83	452,83
5	294	324	5,00	1695,00
5,5	275	381	17,67	8533,00
6	88	305	36,17	22676,50
6,5	0	167	27,83	23129,50
7	0	30	5,00	5180,00
7,5	0	2	0,33	430,67
	∑		**96,00**	**62398,00**

Figure 21: Potential of reduced Bat protection shutdown periods using iSpin

6.2.5 Promote iSpin usage for wind farm performance warranties

Verification that wind turbines meet the contractually warranted performance levels is usually limited to a few wind turbines in a wind farm. This is because turbines for which performance verification is to be provided require free wind sectors that are free of obstacles, meet certain terrain requirements, and are not in the wake of other turbines.

This is becoming increasingly difficult in today's increasingly dense wind farms. The iSpin spinner anemometer with the results from this PTP project now opens up the possibility of determining comparable power curves for every wind turbine in the wind farm, regardless of location.



	Offered today	Technically possible with iSpin
Verification	• 1 or 2 turbines with met mast (sample) • Only turbines with free wind sector • Difficult in complex terrain	• All turbines in wind farm
Time	• Campaign after commissioning	• Turbine lifetime monitoring
Scope	• Availability warranty	• Performance warranty

Figure 22: Better and practically enforceable performance warranties using iSpin

ROMO Wind proposes to adapt the actual methods as stated in the IEC 61400-12-1 [C2], IEC 61400-12-2 [C1] and the best practice for spinner anemometer [B16] to incorporate all wind turbines in a wind farm for the performance assessment as a basis for performance warranties in wind turbine sales contracts:

The principle scheme to determine the actual annual wind park energy production and to compare it with the warranted annual wind park production is shown below. As a pre-condition each of wind park turbines have to be equipped with the iSpin spinner anemometer technology. This enables the measurement of the actual wind speed, wind direction, turbulence intensity, yaw misalignment, inflow angle, nacelle direction, air pressure and air temperature. These values are necessary to calculate for the turbines the 360° power curves $\boldsymbol{PC_{360°,i}}$ in the observation period with the lowest possible uncertainty.

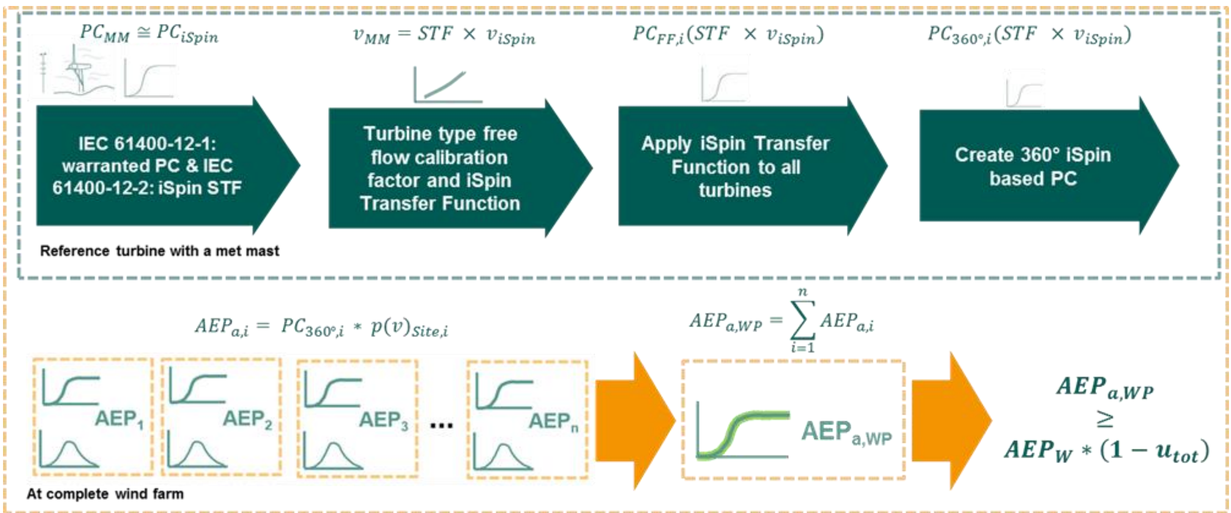


Figure 23: Principle scheme of iSpin based wind farm performance warranty

6.3 Competitive situation

The Performance Transparency Project demonstrated the robustness and transferability of the iSpin measurement characteristic from the calibration situation to the application situation. Furthermore, it showed that power curves based on iSpin “free wind speed” measurements are at the same accuracy level as power curves based on reference measurement systems such as met masts or nacelle lidars.

In terms of competitive situation three different categories can be identified for which the results of the PTP are valuable:

1. Conventional nacelle anemometry (as installed by the OEM)
   Due to the arrangement behind the rotor, the usability of the nacelle anemometer wind speed and wind direction measurements is limited for assessments where measurements of "free wind conditions" are required. In particular, yaw misalignment can severely affect the accuracy of nacelle anemometer measurements and lead to misinterpretations of, for example, turbine performance. In addition, conventional anemometry data can be post-processed by the OEM before it reaches the customer as SCADA data.
   Unlike nacelle anemometer measurements, iSpin spinner anemometer measurements are not affected by downstream effects of the rotor. Together with the traceable calibration and the transferability of the measurement characteristic, iSpin is the better choice to give the customer unbiased and transparent insights into the actual wind conditions and the performance of their turbines.

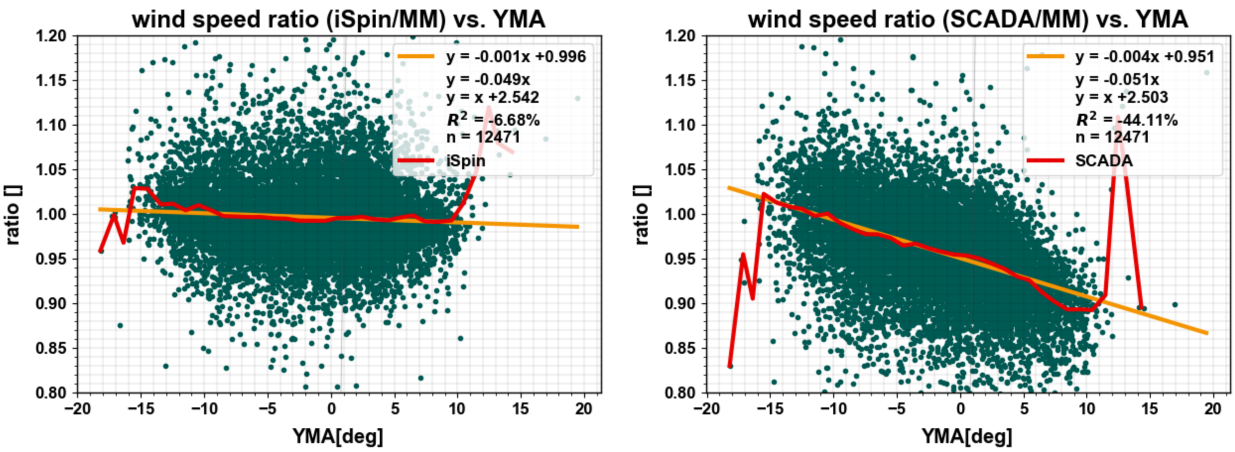


Figure 24: Comparison of "Free wind speed" sensitivity of Spin Spinner Anemometer (left) and Nacelle anemometry (right), based on measurements from PTP Turbine Type A, Complex site

2. Nacelle mounted lidars
   Nacelle-mounted lidars can measure the "free wind speed" in a range of 2 to 4 diameters directly in front of the turbine. The future standard IEC 61400-50-3 [C16] describes in detail the use of remote sensing devices for wind measurements. Unlike iSpin, there is no transfer function and thus no uncertainties related to a transfer function, resulting in an overall lower uncertainty of the "free wind speed" when using nacelle-mounted lidars compared to iSpin. Nevertheless, compliance with the IEC 61400-50-3 standard imposes a high cost and effort in performing wind speed and power curve measurements with nacelle-mounted lidars. This limits their application mainly to certain reference turbines and does not allow scalability to measure or even monitor the performance of all turbines in a wind farm during their lifetime. Furthermore, the application of nacelle-mounted lidars is limited to sectors where all criteria of Table B.1 of IEC 61400-12-2:2017 are met. Wakes also affect nacelle-mounted lidar measurements significantly more than iSpin (see Figure 25).

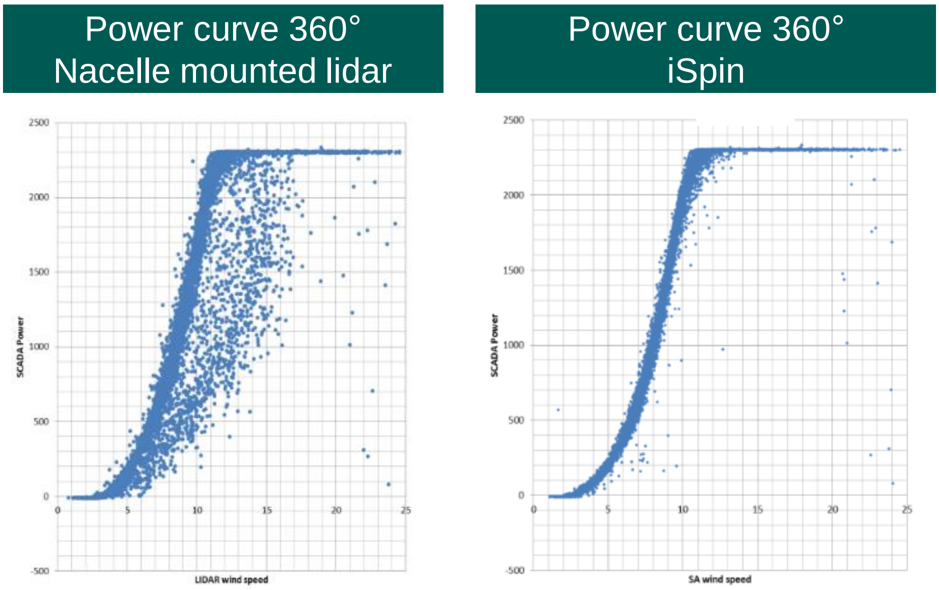


Figure 25: Comparison of 360° power curves measured with nacelle mounted lidar (left) and iSpin (right). Comparison performed at non PTP site.

3. Others
   a. Short range nacelle mounted lidars (measurement range << 2 rotor diameter)
      Like iSpin, short-range lidars basically measure in the induction zone of the turbine, i.e. these devices also require a transfer function that corrects the lidar wind speed measurements to "free wind speed measurements". Here, it can be assumed that similar or even higher uncertainties compared to iSpin for wind speed have to be taken into account when used for e.g. performance analysis. No information is currently available on the transfer function corrections and uncertainties of these devices. In addition, the same application restrictions apply to short-range lidars as to normal nacelle-mounted lidars.
   b. Data evaluation and recommendation based on machine learning
      Data evaluation based on machine learning relies on the (SCADA) data being available for the turbine or wind farm. Without consideration of the wind turbine physics the quality (accuracy and precision) of the used data determines the quality of the output and recommendations. Here, iSpin wind condition measurements like wind speed, turbulence intensity, yaw misalignment and flow inclination can help improve the results of machine learning algorithms.

6.4 Entry and sales barriers

Two major barriers to entry and sales can be identified that the PTP results will be helpful in overcoming:

1. Wind turbine OEMs are still reluctant to accept iSpin for power curve acceptance tests, i.e., this kind of test option as described in IEC 61400-12-2 [C1] is in many cases not included in the power warranty contracts. For most s, the IEC 61400-12-2 standard is not relevant or is not considered applicable for power curve verifications because they are only aware of the high uncertainties caused by the use of conventional nacelle anemometry.
   Here, the DTU Wind Energy reports, and in particular the Spinner Anemometer Best Practice report as the final outcome of the demonstration project, are considered as scientifically sound documents for a) s to re-evaluate the use of spinner anemometers for power curve verification and b) as a means for customers to force s to include power curve verifications based on spinner anemometers in sales contracts.

2. To provide iSpin "free wind speed" measurements it is needed that turbine type specific calibrations are performed using a reference system (met mast or remote sensing device). This is especially problematic for very old turbine types (where such combination of turbine and reference system is no longer available or expensive to achieve) and for new turbine types, where OEMs normally need to be involved.
   Again, the PTP results are considered helpful for to convince OEM with the help of customers and 3rd party consultant to install iSpin spinner anemometer for type specific calibration during the prototype power curve measurement.

6.5 Project results in relation to energy policy objectives

Due to the nature of iSpin of being a wind condition measurement system there is no direct impact of the project results in relation to energy policy objectives. Nevertheless, as shown in Figure 13, the use of iSpin can support to lift the performance characteristic of a wind turbine to the projected design level and finally achieved an energy production for a specific site as planned. Based on accurate, precise and robust iSpin measurements it is furthermore possible to distinguish between the wind conditions affecting a turbine and the actual performance characteristic of the wind turbine. This allows to get a transparent insight on what is causing deviations of the real energy yield compared to the forecasted production.

7. Project conclusion and perspective

7.1 Conclusions

7.1.1 DNV-GL conclusions

Experiences with iSpin power curve measurements indicate advantages compared to met mast power curves in terms of reduced scatter. This advantage makes the iSpin a good choice for relative measurements, e.g. evaluating modifications of the turbine.

Differences between the STFs generated for the evaluated turbine type at different sites (flat, offshore, complex) where found to be in the range of 2%.

Seasonal variations in the STF generated for on turbine type at different sites (flat, semi-complex, complex) where found to be in the range of 2%. Nevertheless, according DNV-GL the standardized 2% uncertainty stated in IEC 61400-12-2 /7/ does not seem applicable for the three evaluated sites. It rather seems applicable to fully replace the seasonality uncertainty by uncertainties related to the individual parameters that might change over the course of a year.

Main sensitivity of iSpin STF and subsequently iSpin based "free wind speed" is the turbulence intensity, followed by yaw misalignment.

STF robustness regarding measurements in wake is of reduced applicability. However, DNV GL believes that under wake conditions the iSpin system will provide a more accurate hub height wind measurement than a nearby met mast or a conventional turbine nacelle anemometer. Hence, it is useful for special applications or overview measurements, e.g. for monitoring performance degradation, qualitative wake turbulence analysis etc

As a recommendation a flat site should always be preferred to generate an STF. Shear should always be monitored, whether it influences the STF

For more details, please review [B4].

7.1.2 DWG conclusions

Differences between STF generated for on turbine type at different sites (flat, semi-complex, complex) where found to be in the range of 2%. According to DWG the STF are in fair agreement with each other reflecting the uncertainties in the reference measurement itself.

Seasonal variations in the STF generated for on turbine type at different sites (flat, semi-complex, complex) where found to be in the range of 2%.

Main sensitivity of iSpin STF and subsequently iSpin based “free wind speed” is the turbulence intensity. No further STF sensitivity was found with respect to all other variables investigated.

The stability assessment of iSpin measurements in relation to site effects provided positive results. The self-consistency tests applied to the SPC (spinner Power Curve) measurements suggest that the limitations required by the norm in terms of terrain class could be relaxed.

iSpin should be not used to measure power curves under wake conditions

iSpin is considered as suitable tool to assess performance changes.

For more details, please review [B8].

7.1.3 DTU conclusions

STF robustness for flat and semi-complex sites (see also [B11]):

STF changed with turbulence intensity, temperature, air density, turbine yaw misalignment and wind inflow angle, but changes (uncertainties) due to temperature, air density and flow inclination are already accounted for by the instrument’s “operational” uncertainties, obtained from the cup classification (of the met mast) and the spinner anemometer classification

Finally, DTU saw sensitivities of the STF due to turbulence intensity and yaw misalignment. DTU quantified the STF uncertainty due to sensitivity to both environmental variables as 2%-2.2% of the “free wind speed”, for yaw misalignment angles between -17° and 20°, and turbulence intensities between 0% and 30%.

STF robustness for offshore site (see also [B12]):

The “seasonal” analyses (i.e., comparison of STFs generated in different time periods) showed that the differences between STFs were within ±2% of the reference wind speed. Moreover, the results might suggest that this range may be close to ±1% if the sensitivity to shear is reduced (e.g., by lidar corrections).

Regarding STF transferability between different sites (flat terrain, complex terrain and offshore for which turbine type A was evaluated), DTU concluded that the differences between the STFs from the three terrain types would lie within ±2% of the free wind speed

Based on these results, DTU suggest to use a STF uncertainty term $u_{M2,i}$ specifically for spinner anemometry, that accounts for the STF sensitivity to environmental variables in inter- and intra- turbine applications. The suggested value is ±2% of the “free wind speed”, for all the PTP sites.

STF robustness for complex sites (see also [B13]):

STF changed with turbulence intensity, wind shear temperature, air density, turbine yaw misalignment and wind inflow angle, but changes (uncertainties) due to temperature, air density and flow inclination are already accounted for by the instruments’ “operational” uncertainties, obtained from the cup classification (of the met mast) and the spinner anemometer classification

Finally, DTU saw sensitivities of the STF due to turbulence intensity, wind shear and yaw misalignment. DTU quantified the STF uncertainty due to sensitivity to these environmental variables as 1.7% of the free wind speed.

Overall conclusion

The IEC 61400-12-2 standard [1] requires an uncertainty due to seasonal variability being added to the STF uncertainty budget ($u_{M2,i}$). The seasonal variability is an uncertainty component that is not part of the measurement uncertainty. It is an uncertainty component that is added when the measured STF is extrapolated to be representative for a whole year. The way it is described in the standard is: "*Any NTF" [STF] "measured at different times of the year using same equipment will give different results. This is a guess/estimate of the magnitude of this effect, but the actual uncertainty will depend on the site and the complexity of the wind. The longer " [the STF] " dataset the lower this uncertainty will be*".

DTU proposes a new name and slight interpretation change for this uncertainty component $u_{M2,i}$. To DTU's understanding, the main issue that this uncertainty term should account for is that a STF will likely be applied in different conditions (in terms of environmental variables like turbulence intensity, wind inflow angle, etc) from those in which it was generated. So, this term accounts for:

- the variability of STF over time or with respect to changes in environmental conditions (e.g., turbulence, wind inflow angle, etc.) for a given turbine, on which the STF was generated. This uncertainty is relevant for the so-called "intra-turbine" power curve measurements. That is, given a turbine for which a STF was generated (in that same turbine), a power curve (i.e., the STF application) takes place at different time, or at different environmental conditions from those where the STF was generated.
- the variability when transferring a STF to another turbine of the same type, in the same or another wind farm. This is relevant for "inter-turbine" power curve measurements. That is, a power curve (i.e., the STF application) takes place at a different turbine, and either at a different time or at different environmental conditions from those where the STF was generated.

In their revised best practice method description for Spinner Anemometry DTU used the long-term demonstration datasets obtained in the PTP and quantified term $u_{M2,i}$ specifically for spinner anemometry, by investigating the STF sensitivity to environmental variables. The impact of the turbulence intensity was the dominant factor, especially in flat sites. For some complex sites the main influence was related to the inflow angle and shear. The suggested value for this uncertainty, based on PTP data, is 2% of the "free wind speed". A sensitivity analysis on the STF dataset is recommended to confirm or update this uncertainty value.

According DTU the uncertainty $u_{M2,i}$ should not account for sensitivities to environmental variables of the instruments (cup or spinner anemometer) used to derive the STF. Those instrument sensitivities are already accounted for in components $u_{FS2,i}$ and $u_{N2,i}$ (see [B15]).

Following DTU any turbine yaw errors should be corrected prior to performing a STF measurement. In this case, the uncertainty component due to high yaw misalignment ($u_{M2\_YE,i}$) may be dismissed. This term should be used only in cases in which significant yaw misalignment is measured during the STF campaign. The proposed value for this uncertainty is based on the PTP data [B11]. If $u_{M2\_YE,i}$ is required, we advise users to assess the magnitude of this uncertainty based on their measurement data; for example through a sensitivity analysis similar to the one presented in [B11].

For more details, please review [B16].

7.2 Next steps

7.2.1 Reduction of method uncertainty "Variation to inflow" for iSpin by combining iSpin with blade bending measurements

The method uncertainty "Variation to rotor inflow" in IEC 61400-12-2 (table G.3) /7/ with default 2% addresses the limitation that wind speed is only measured at hub height, which may not accurately represent the kinetic energy available across the rotor area.

Main lack of Spinner Anemometry measurement is that it is a "point" measurement in hub height that doesn't include information about the shear and veer affecting the entire rotor. This becomes increasingly important as rotor diameter steadily grow and for hub height "point" measurement only an additional uncertainty has to be considered for the power curve measurement.

To overcome this issue a combination of iSpin wind condition measurements and measurements at the rotor blades (like e.g., blade root bending measurement, blade bending line measurements or acceleration measurements along the blade axis) is planned to be tested. The iSpin wind conditions measured at the rotor center will act in this combination as absolute wind speed measurement whereas blade measurements will deliver the shear and veer information across the rotor as differential value relative to the iSpin measurement.

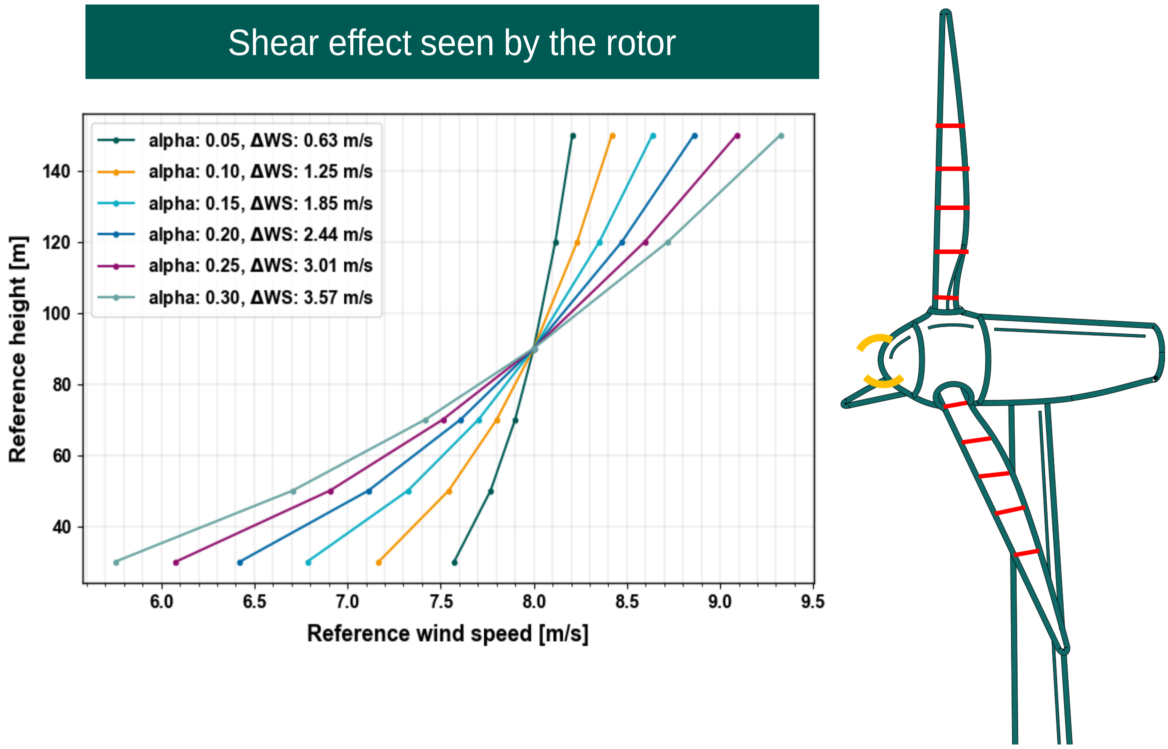


Figure 26: Combination of iSpin measurement system (orange) with rotor blade measurements system (red)

7.2.2 Detailed analysis of performance measurement capabilities under wake conditions

During the demonstration project the capability of iSpin to measure wind speed under 360° inflow conditions was evaluated by one of the 3rd party consultants for sites of different complexity. This evaluation showed that the iSpin measurements are nearly unaffected by terrain effects (see Figure 27 where ±2% band around ratio 1 was not exceeded), but are affected by wakes of other turbines (see Figure 28 where ±2% band around ratio 1 was exceeded).

Although iSpin wind speed measurements are affected the impact on the performance evaluations seems not to be affected in the same order. To evaluate this discrepancy more detailed analyses will be performed based on the data being collected during PTP.

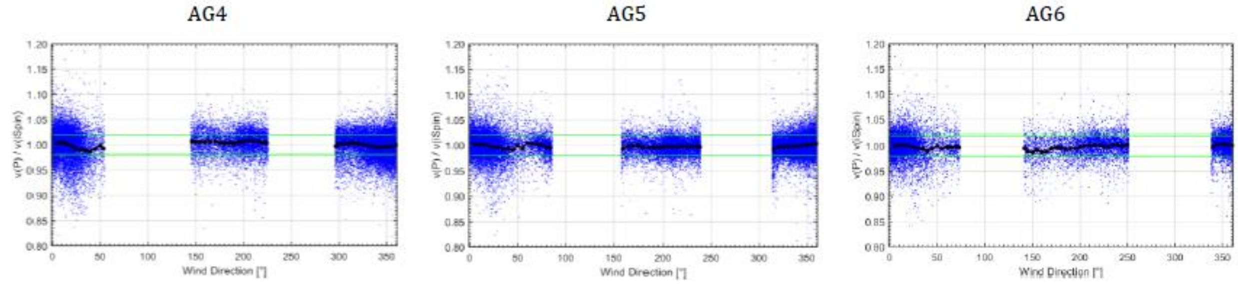


Figure 27: Self-consistency check for SPC without wake sectors (Turbine type B, semi-complex terrain) [C12]

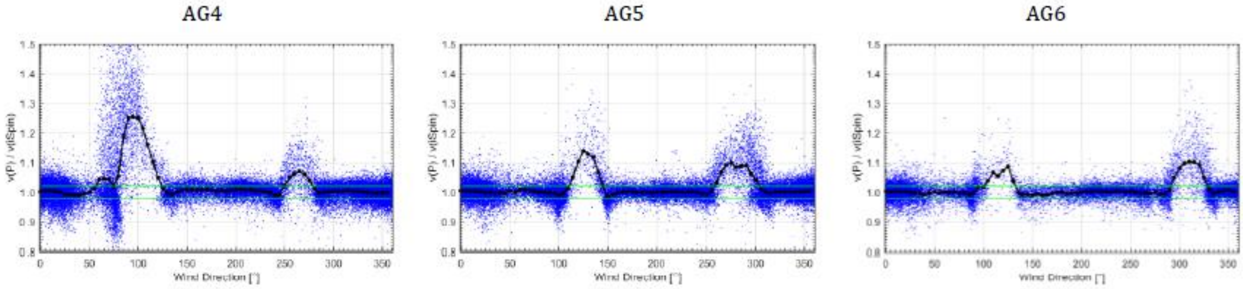


Figure 28: Self-consitency check for SPC with wake sectors (Turbine type B, semi-complex terrain) [C12]

8. Appendices

8.1 Deliverables

[B1] DNV-GL, Final report 10108795-R-1-A, Rev. A:
iSpin PTP Project: Measurement results and evaluation - Turbine type A, complex test site, 05/2021

[B2] DNV-GL, Final report 10108795-R-2-A, Rev. A:
iSpin PTP Project: Measurement results and evaluation - Turbine type A, offshore test site, 05/2021

[B3] DNV-GL, Final report 10108795-R-3-A, Rev. A:
iSpin PTP Project: Measurement results and evaluation - Turbine type A, flat site, 05/2021

[B4] DNV-GL, Final report 10108795-R-4-A, Rev. A:
"iSpin PTP Project: Summary of results and evaluation", 05/2021

[B5] Deutsche WindGuard, Final report PP19067.A0:
Performance Transparency Project. Evaluation of Spinner Anemometer Transfer Function and its Stability – Turbine type B, flat site, 12/2019,

[B6] Deutsche WindGuard, Final report PP19003.A1:
Performance Transparency Project. Evaluation of Spinner Anemometer Transfer Function and its Stability – Turbine type B, semi-complex site, 10/2019

[B7] Deutsche WindGuard, Final report PP20016.A2:
Performance Transparency Project. Evaluation of Spinner Anemometer Transfer Function and its Stability – Turbine type B, complex site, 12/2020

[B8] Deutsche WindGuard, Final report PP20056.A1:
"Performance Transparency Project. Evaluation of Spinner Anemometer Transfer Function and its Stability, 07/2021

[B9] UL International, Draft Presentation:
PTP – Romo Wind Overview / Results – Turbine type C, flat site, 02/2021

[B10] UL International, Draft Presentation:
PTP – Romo Wind Overview / Results – Turbine type C, complex site, 02/2021

[B11] DTU Wind Energy, Report E-0226, "PTP Deliverable 7.1 – STF Uncertainty Analysis in flat and semi-complex terrain sites", 04/2021

[B12] DTU Wind Energy, Report E-0227, "PTP Deliverable 7.2 – STF Uncertainty Analysis in offshore sites", 07/2021

[B13] DTU Wind Energy, Report E-0228, "PTP Deliverable 7.3 – STF Uncertainty Analysis in a complex terrain site", 07/2021

[B14] DTU Wind Energy, Report E-0229, "PTP Deliverable 7.4 – Recommendation for re-working IEC 61400-12-2 standard concerning uncertainty components using spinner anemometry", 07/2021

[B15] DTU Wind Energy, Report E-0165 Version1, PTP Deliverable 8.1, Spinner Anemometry – Best Practice", DTU Wind 04/2018

[B16] DTU Wind Energy, Final report E0165 Version 2, "PTP Deliverable 8.2 – Spinner Anemometry – Best Practice Version 2", 07/2021

[B17] DTU Wind Energy, Report E-0230, PTP Deliverable 8.3: "Recommendation for re-working IEC 61400-12-2 methods for the use of spinner anemometry", 07/2021

8.2 Other documents

[C1] International Electrotechnical Commission, International Standard IEC 61400: Wind turbines – Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry. 2013.

[C2] International Electrotechnical Commission, International Standard IEC 61400: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. 2005.

[C3] International Electrotechnical Commission, International Standard IEC 61400: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. 2017.

[C4] T. F. Pedersen, G. Demurtas, and F. Zahle, "Calibration of a spinner anemometer for yaw misalignment measurements," Wind Energy, vol. 18, no. 11, pp. 1933–1952, 2014, doi: 10.1002/we.1798.

[C5] ROMO Wind A/S, Requirement Specification: "Requirements for Performance Transparency Project and Necessary Information per PTP Wind turbine", 02/2017

[C6] ROMO Wind A/S, Data sheet, "iSpin V3", 05/2017

[C7] Deutsche WindGuard Wind Tunnel Services GmbH, Calibration certificate for iSpin V3 sensor, SN3011715039, 05/2017

[C8] ROMO Wind A/S, Data sheet, "iSpin 4", 10/2019

[C9] Deutsche WindGuard Wind Tunnel Services GmbH, Calibration certificate for iSpin V4 sensor 1511818027, 02/2019

[C10] DNV-GL, Final report for turbine type A in complex terrain: 10108795-R-1-A, Rev.A, 05/21

[C11] Deutsche WindGuard, Final report for turbine type B in complex terrain: PP20016.A2, 12/20

[C12] Deutsche WindGuard, Final report for turbine type B in semi-complex terrain: PP19003.A1, 10/19

[C13] UL International, Draft presentation for turbine type C in flat terrain: PTP_UL_presentation_2021-02-0

[C14] International Electrotechnical Commission, International Standard IEC 61400: Wind turbines – Part 28: Through-life management and life extension of wind farms, 88/798/CD

[C15] S.K. Kanev, F.J: Savenije, W.P: Engels, "Active wake control: An approach to optimize the lifetime operation of wind farms", Wind Energy, 2018; 21:488-501

[C16] International Electrotechnical Commission, International Standard IEC 61400: Wind energy generation systems – Part 50-3: Use of nacelle mounted lidars for wind measurements, 88/778/CDV

[C17] WindEurope Technology Workshop 2021, Italy, 09/21, K. Hermans et al., Poster:
"Power performance assessment and optimization using spinner anemometers and nacelle LiDAR systems"