Retrofit Yaw Control Kits for higher power output

Final report

DRAFT

DTU Wind Energy
Department of Wind Energy

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1. Project details

Project title	Retrofit udkrøjningskit til højere el-produktion
Project identification (program abbrev. and file)	Retrofit Yaw Control Kits for higher power output
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	ROMO Wind A/S. Olof Palmes Alle 47 8200 Aarhus N
Project partners	Vattenfall A/S and DTU Wind Energy
CVR (central business register)	33964811
Date for submission	5 March 2012

2. Short description of project objective and results

2.1 English description

The project objective was to further develop and demonstrate the spinner anemometer technology ("iSpin"), in collaboration between Vattenfall, DTU Wind Energy and ROMO Wind. A technical solution using iSpin measurements for automatic yaw misalignment correction was to be developed (iSpin Yaw), and the iSpin capability to measure wind turbine performance was to be documented. In addition, a cost effective iSpin product was to be developed.

An electronic iSpin Yaw version was developed and is now being tested in a final phase. In addition, the unique capability of iSpin for measuring wind turbine performance and yaw misalignment also under disturbed wind conditions was documented. The results indicated that the iSpin technology may be universally capable of measuring wind turbine performance of all wind turbines in wind farms independently of their terrain location, but further wind farm studies are needed to prove this. ROMO Wind also successfully developed a robust and cost effective iSpin industry product and associated data handling solution.

2.2 Danish description

Projektformålet var at videreudvikle og -demonstrere spinner anemometer teknologien ("iSpin"), i et samarbejde mellem Vattenfall, DTU Wind Energy og ROMO Wind. Der skulle udvikles en teknisk løsning, som baseret på iSpin målinger kunne benyttes til automatisk at korrigere vindmøllekrøjefejl (iSpin Yaw) og iSpin's evne til at måle vindmøllers effektivitet (performance) skulle dokumenteres. Endvidere skulle der udvikles et omkostningseffektivt iSpin produkt med tilhørende databehandling.

En elektronisk iSpin Yaw version blev udviklet og er nu under afsluttende afprøvning. Endvidere blev iSpin's unikke evne til præcist at måle vindmøllers performance og krøjefejl selv i forstyrrede vindforhold vist og dokumenteret. Resultaterne tydede på, at iSpin er universelt i stand til at måle vindmølle-performance på alle vind møller i vindfarme uafhængigt af deres terrænplacering, men yderligere multi-vindfarmstudier er nødvendige for at vise dette. ROMO Wind udviklede også en robust og omkostningsoptimeret industriprodukt samt tilhørende datahåndteringsløsning.

3. Executive summary

This collaboration project between Vattenfall A/S, DTU Wind Energy and ROMO Wind A/S, has been focusing on demonstrating and further technically developing the spinner anemometer technology ("iSpin") that in 2004 was invented and patented by DTU Wind Energy and in 2011 acquired by ROMO Wind.

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The focus of the project was partly to develop and demonstrate a new application of the iSpin technology (iSpin Yaw), which based on iSpin measurements could be used for automatic correction of wind turbine yaw misalignment, and partly to document the use of iSpin for measuring and monitoring the wind turbine power curve and other wind conditions of importance for wind park operation. In addition, the purpose was in general to develop and demonstrate an industry compliant, robust and cost effective iSpin product solution and data-handling tool.

During the project, it was established that an electronic rather than the originally planned mechanical iSpin Yaw solution was a commercially feasible version. The electronic solution uses iSpin measurements to improve the existing wind direction sensor signal before entering the wind turbine controller. A version was subsequently developed and is now in a final field-testing to be completed by the end of 2016. In the project period ROMO Wind independently showed after having analysed more than 300 wind turbines using iSpin that more than half of the turbines show so significant yaw misalignment that correction will lead to on average approximately 2% more annual energy production as well as to reduction of loads.

As part of the project a thorough field iSpin analysis study on all turbines in a wind farm owned by Vattenfall and located in flat terrain, was conducted. On one of the turbines in the wind farm, the wind measurement capability of iSpin was directly compared to other technologies for measuring the wind hitting the wind turbine: A nacelle lidar, a met-mast and the wind turbine nacelle anemometer.

It was showed when measuring in the open, undisturbed wind sector of the wind turbine, that the met-mast, the nacelle lidar and iSpin measure the turbine power curve with comparable measurement uncertainties. So all three methods could in theory be used for power curve verification. However, only iSpin was also able to measure yaw misalignment, other flow inclination angles, the wind speed – and hence the power curve – as well as turbulence intensity with high precision when the turbine was exposed to disturbed wind conditions induced by wakes from the other wind turbines in the wind farm. When all turbines were performing optimally in the wind farm, iSpin was able to measure the wind turbine power curves on all wind turbines irrespectively of wake conditions and to show that they were varying less than 0.3% in annual energy production from the wind farm reference turbine verified using the met-mast. No other technology on the market is capable of this.

This means that iSpin can be used for performance measurement and verification on all wind turbines in a wind farm and over its entire lifetime - at least in a flat terrain as demonstrated in this project. However, based on these observations it seems likely that iSpin could also be capable of measuring this in complex (mountains and hills) and semi-complex (forested) terrain types as well as in offshore wind farms. This would be of very considerable commercial value, because this has so far not been possible to accurately monitor and verify wind turbines delivered by wind turbine manufacturers or to monitor their performance over their lifetime.

ROMO therefore wants to demonstrate this potential universal iSpin capability in a subsequent project of a much larger scale using iSpin for analysing wind farm performance with different turbines types and on wind farms in all relevant terrain types. A new EUDP application in collaboration with DTU has therefore been submitted for this purpose.

Lastly but not least, ROMO Wind during the project period completed the development of a highly flexible hardware and software iSpin product solution, which is very robust, has close to 100% data availability and is highly cost optimized. This final, industrialised, version of the iSpin technology will be ready for rollout in large scale both for new and already installed wind turbines.

4. Project objectives

The fundamental problem to be solved by this project, which began on 4 July 2012, is the fact that a poor measurement location of the sensors on top of the nacelle behind the wind turbine rotor of all current wind turbines is known to produce yaw errors (yaw misalignment). This leads to production losses and increased turbine loads. Importantly, it also means that the current nacelle anemometer sensors cannot report reliable power curves via the wind turbine SCADA system, which makes the operator unable to monitor, optimize and intervene in case of wind turbine underperformance.

Yaw control and performance measurement of wind turbines is critically dependent on correct wind direction and speed measurements. The position of wind sensors today is influenced by several unpredictable aerodynamic phenomena created by the blades, the root vortex and by the nacelles itself due to complex terrain and wakes from other wind turbines. This is known to disturb the wind nacelle sensor measurements. Consequently, the current turbine wind sensors are not capable of optimally controlling the wind turbine yawing, to reliably record the turbine power curve, nor to measure the turbulence intensity hitting the turbine.

In contrast, the spinner anemometer – later named "iSpin" after being acquired by ROMO Wind ("ROMO") from DTU Wind energy in 2011 – is placed on the turbine spinner in front of the rotor, where flow conditions are understood and hence can be corrected for. The iSpin measures the speed of the wind flow passing over the spinner for accurate determination of yaw error, wind speed and flow inclination angle. When the wind runs directly along the rotor axis, i.e. the nacelle is aligned to the wind direction, all the iSpin wind sensors experience the same wind speed (yaw error = 0 degrees). When the wind angle of attack is changing, the wind speeds at the individual sensors - rotating with the spinner - are changing. This is used to accurately calculate the attack wind angle on the turbine, and since the iSpin also has build-in accelerometers, the horizontal wind attack angle – the yaw error – can be accurately determined. The iSpin uses proven sonic technology, which is already routinely used in nacelle anemometry, and up to three sonic instruments are mounted on the spinner.

The ability of the iSpin to accurately detect yaw errors has been thoroughly proven by DTU in demonstration projects over the past 6 years, including in the EUDP project "Forbedring af vindmølleparkers ydelse med spinder anemometri", EUDP jr. no. ENS-64009-0103. The iSpin technology concept, which was used in the mechanical yaw control kits to be developed in this project, was scientifically thus already quite mature, but significant additional technology was needed to make the technology practically useable.

The iSpin accurately detects yaw misalignment, but the technology, when acquired by ROMO had not yet been commercially successful for this purpose and it had not yet been developed also for power curve measurement. Additional user-friendly technology was therefore necessary to enable the iSpin to automatically detect and correct the yaw errors and enable performance monitoring, which was the purpose of this project.

The objective of this project was initially to develop mechanical yaw misalignment correction kits and subsequently demonstrate their value by documenting the provided extra power, and their compliance with the different harsh climatic and terrain conditions required by equipment used in the wind power industry.

4.1 Project period from H2 2012 to H1 2013

Initially it was planned to develop a mechanical yaw misalignment kit based on a device capable of mechanically correcting the wind turbine wind direction sensor (making a measurement offset) governed by yaw misalignment measurements provided by iSpin. ROMO had filed a patent application on such a device in March 2012. The project, which began in the second half of 2012, had the following main initial objectives:

- Development of two prototypes and subsequently an industrial scale kit version ("iSpin 1 Kit" - later re-named to: "iSpin Yaw")
- Demonstrate and document the iSpin Yaw Kits on ROMO Wind's test turbine and in Vattenfall's wind farm already installed with iSpin in the on-going EUDP project: ""Forbedring af vindmølleparkers ydelse med spinder anemometri".
- Laboratory test and lifetime estimate the iSpin Yaw Kit at various climatic conditions and update and optimize the design based on the results.
- Extensively field-test the iSpin Yaw Kit in wind farms located in different climates and terrains.
- Conduct preparative investigations in collaboration with DTU Wind Energy for eventual development of even more advanced yaw control kits (iSpin 2 & 3 Kits). This concerned performance measurement and potential turbine control.

The first project period beginning in second half of 2012 and continuing through the entire project period was focused on improving the technical functionality of iSpin sensor associated hardware and software including experimenting with various internal and external data communication setups from the iSpin sensors as well as reducing product cost. ROMO initially developed a data logger named "iSpin Brain", which were mounted on 9 wind turbines owned by Vattenfall located in the wind farm "Vedersø Kær". Here it was confirmed that a majority of the wind turbines had significant yaw misalignment problems with an average error of more than 6 degrees. This is exemplified in **Figure 1** on the turbine, which had the largest yaw misalignment.

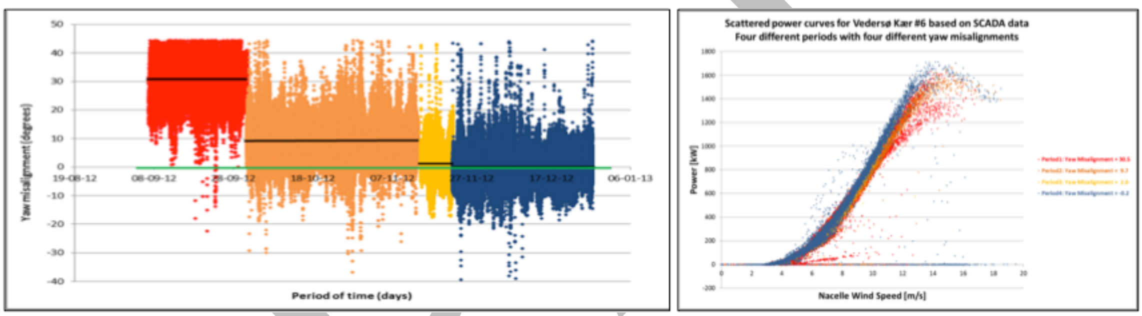

***Figure 1: Left figure**: Gradual correction of the average yaw misalignment on wind turbine #6 from 30.5, 9.7, 2.0 until fully corrected -0.2 degrees. **Right figure:** The change is also clearly reflected in the turbine power curve gradually moving to the left showing the increased turbine performance as a result of yaw misalignment correction.*

During this period it was shown by ROMO using relative power curve analysis of all wind turbines in Vedersø Kær as well as also independently by Vattenfall using side-by-side performance analysis that the additional Annual Energy Production (AEP) gain from the wind farm after correcting the yaw misalignment was about 2.5%. This is in full accordance with the expected $\cos^2$-relationship between AEP gain and degrees in yaw misalignment correction. In the same period GL Garrad Hassan (now DNV_GL) as a third independent party also reviewed the iSpin technology and confirmed its measurement capabilities as well as the AEP cos2-relationship to yaw misalignment[1]. This information had initially significant importance of ROMO's marketing of iSpin for yaw misalignment detection and correction. In 2015 DNV_GL again reconfirmed the iSpin technology as well as the ROMO data showing (based on iSpin yaw misalignment analysis on 155 wind turbines) that more than half of wind turbines

[1] Technology review of the ROMO Wind spinner anemometer Report No. Aaa789-DKHI-R-01. Lars Falbe-Hansen. GL Garrad Hassan. September 2012

have yaw misalignment, which if corrected can provide about 2% more AEP[2]. The business case for yaw misalignment was thus clearly confirmed.

During the remaining part of 2012 and the first half of 2013 a so-called "yaw robot" prototype was developed and tested. This mechanical device or servomechanism made in stainless steel was mounted underneath the existing wind direction sensor, with the vision to mechanically make an appropriate sensor offset, when demanded by the iSpin sensor signal. This is illustrated in Figure 2.

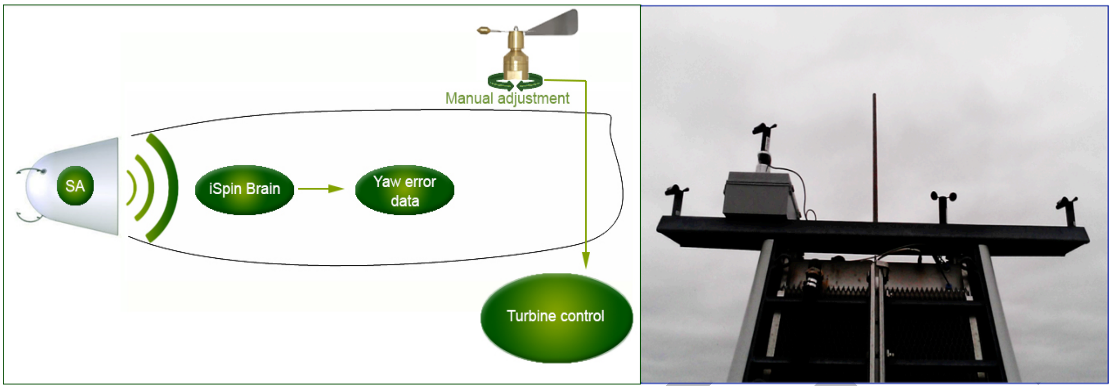

*Figure 2: **Left figure**: The iSpin (SA) transfers yaw misalignment data from the spinner via WiFi. The data are processed in the iSpin Brain inside the nacelle and from here fed to the "servo mechanism" or yaw robot, which makes an appropriate offset of the sensor hereby changing the signal entering the turbine control system. **Right figure**: The prototype yaw robot mounted on a wind turbine in Denmark.*

However during spring 2013 it became clear that the mechanical yaw robot was not a sustainable solution that could live up to the strict quality criteria for outdoor wind turbine equipment. It turned out to be very difficult to protect it from the weather conditions and keep it watertight. After a period of rain it completely froze, and ROMO ran out of ideas how to improve it. It was therefore decided in mid 2013 to terminate this development.

In the same period ROMO experienced increasing technical problems with the iSpin Brain electronics used for internal Wi-Fi data communication of iSpin data from the spinner to the nacelle and from iSpin Brain via 3G external data communication to ROMO in Aarhus. The Wi-Fi solution was not stable enough and the iSpin Brain software could not be remotely updated. There were also data time synchronisation issues and the Microsoft industrial computer used was not regarded sufficiently stable for long term iSpin data monitoring. ROMO needed a more professional and long-term sustainable solution.

Furthermore, DTU Wind energy developed a new and much easier iSpin calibration method for yaw misalignment measurement[3]. This completely removed the need for a nacelle lidar or met-mast when calibrating the iSpin for this purpose.

Very importantly, iSpin was accepted in the new IEC61400-12-2 standard for performance measurement on wind turbines[4] and very recently a clarification sheet was published by the IEC committee

[2] Review of the spinner anemometer from ROMO Wind, iSpin. Report No. 113605-DKAR-R-01.. Lars Falbe-Hansen. DNV-GL. March 2015.
[3] Calibration Procedure for Spinner Anemometer Yaw Error Measurements. Troels F. Pedersen, Giorgio Demurtas. DTU Wind Energy I-0082. March 2013

describing iSpin specific calibration procedures in order to measure the wind turbine power curve according to the IEC standard[5]. This was received well in the wind power market, and got ROMO to focus more attention on the potential ability of iSpin to measure, monitor and report wind turbine power curves.

4.2 Project period from H2 2013 to H1 2014

As alternative patent application claims for an iSpin measurement guided mechanical modification of the wind sensor position (the yaw robot), ROMO had fortunately also claimed iSpin measurement guided electronic modification of wind sensor signal before entering the turbine control system. In mid 2013 it was therefore decided to apply EUDP to turn the project towards developing an electronic iSpin Yaw solution since an electronic "virtual" yaw robot is much more robust and furthermore located inside the nacelle in the iSpin Brain. This was accepted by EUDP, but it was thus more or less back to "square one" for the yaw robot. EUDP accepted a project extension to the end of 2014.

At the same time ROMO signed up with Mita-Teknik to develop a more cost effective and stable iSpin Brain solution. It was still like the former iSpin Brain located inside the nacelle communicating with the iSpin sensor via Wi-Fi, but more stable electronics and processers were used.

The Mita-Teknik iSpin Brain product should then also harbour the electronic iSpin Yaw software. The iSpin with the new Mita-Teknik called iSpin Brain was successfully launched at the EWEA conference in Barcelona in March 2014. The development of the iSpin Yaw software, which was anticipated to be developed within this period, was, however, delayed due to the focus on completing the basic functions of the iSpin Brain hardware and software first. In this period it was also planned to install iSpin Yaw on 1-2 wind turbines beginning on a Vestas V80 turbine owned by Vattenfall and then proceeding to another Vattenfall owned wind turbine. For the same reason this was also not done within this period.

With the new iSpin Brain product as well as the inclusion of iSpin in the IEC standard for performance measurement EUDP also agreed to focus the project even more on using iSpin for performance measurement. As of today only a couple of wind turbines have their power curve tested at wind farm commissioning due to the high cost and limited technological capabilities of the industry standard met-mast. The met-mast can e.g. usually not be used in complex terrains or inside the wind farm if affected by wakes from other turbines. It can also not be used in offshore wind farms.

Vattenfall agreed as part of this project to have yet another wind farm, Nørrekær Enge, equipped with iSpin with the purpose of measuring both yaw misalignment as well as power curves on all 13 Siemens 2.3 wind turbines. This would also be the subsequent wind turbine ROMO would install the electronic iSpin Yaw on. However, because of a major re-organisation process within Vattenfall the decision process was dragged out, which unfortunately further delayed the project. EUDP therefore accepted in May 2014 to extend the project until 30 June 2015.

In a EUDP unrelated commercial project Vattenfall furthermore agreed to have iSpin permanently installed on all their Nordic onshore wind turbines – in total 69 wind turbines. This was the first larger rollout order of the iSpin technology ROMO experienced.

4 *Power performance of electricity producing wind turbines based on nacelle anemometry. The IEC 61400-12-2 standard for performance measurement of wind turbines. Edition 1, March 2013*

5 *Use of spinner anemometers, CSH001, IECRE, November 2015*

4.3 Project period from H2 2014 to H1 2015

In this period ROMO's statistic for wind turbines with yaw misalignment expanded significantly because ROMO was offering customers iSpin with the new Mita-Teknik iSpin Brain. Typically ROMO chose to lease the equipment against a monthly service fee or to conduct yaw misalignment detection and correction campaigns. Figure 3 shows the yaw misalignment statistic status in February 2015:

ROMO's static yaw misalignment statistics (152 wind turbines)					
Static yaw misalignment	<4°	4°- 8°	8°-12°	12°-16°	>16°
Distribution	38%	28%	19%	9%	2%

Figure 3: The distribution of yaw misalignment among randomly selected turbines >2MW size. It is clear that more than half of the turbines have more than 4-degrees yaw misalignment. If corrected about 2% more AEP would become available.

So still today, where there is now more than 300 wind turbines in the ROMO yaw misalignment statistic, it is clear that about half of wind turbines have significant average yaw misalignment and that the business case holds. However, it is also clear that the problem varies a lot depending on turbine brand. Below in Figure 4 is anonymously shown the average (static) yaw misalignment problem distributed on a total of 39 wind turbine types.

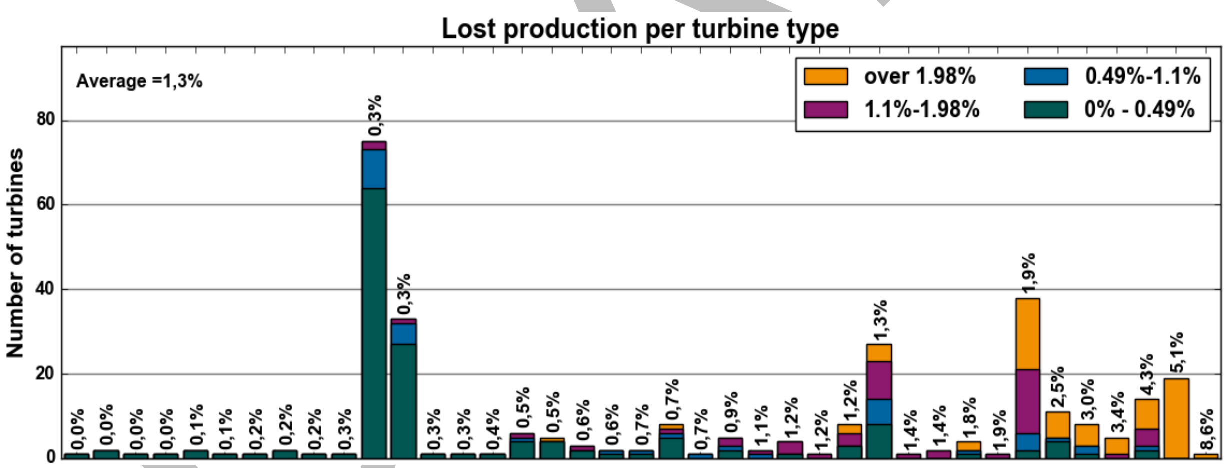

Figure 4: Distribution of static yaw misalignment problems on 39 different wind turbine types. Each column is a turbine type. Some turbines have been tested in large numbers (X-axis), whereas others in a too low number to quantify the problem. It can be seen though, that while some turbines show higher yaw misalignment problems other turbines have much less. There is a tendency that older turbines have worse problems than newer, but ROMO also sees problems with new and large wind turbines.

In this process ROMO also began to get more quantitative insight in the dynamic yawing capabilities (the yawing variation around the average yaw misalignment) of the various turbine brands, and a pattern emerged as shown in Figure 5.

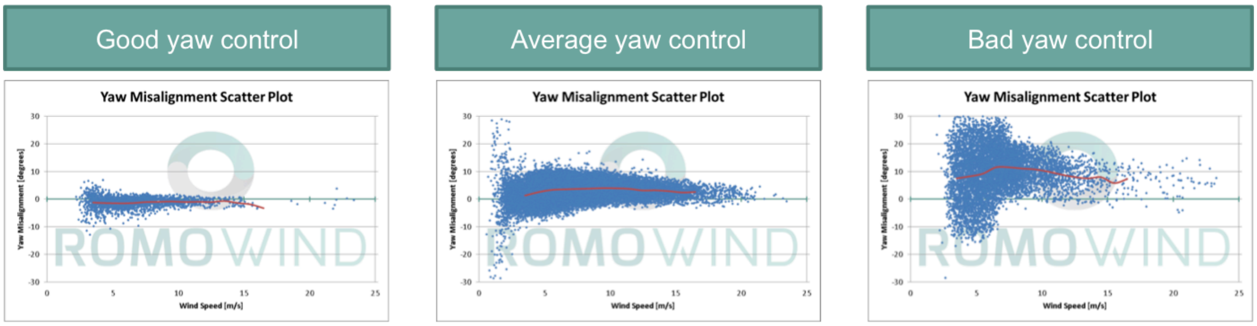

Figure 5: The yawing capabilities of wind turbines. The three panels above show typical 10 min yaw misalignment values (Y-axis) as a function of wind speed (X-axis). The yawing capability of the typical wind turbine is shown in the mid panel. The left panel shows a turbine with unusual good yawing capabilities and the right panel a turbine with unusual poor yaw misalignment capability.

Most modern wind turbines have a yaw variation of +/- 8 degrees. It is very likely that the use of iSpin Yaw could further reduce this variation, which might also reduce the turbine loads. However, if reduced to the level seen on the best wind turbines illustrated in the left panel, it would according to the cos²-relationship about yaw misalignment and AEP gain only provide about 0.2-3% more AEP. If the wind turbine shown in the right panel was improved to the level shown in the mid panel the additional AEP gain would be in the order of 1.5 - 2%. This is significant, but according to ROMO's observations it is only a minority of these turbines on the market having such severe problems. So where there a large and robust market for yaw misalignment detection and performance monitoring the market for active yaw control using iSpin Yaw seemed to be much smaller than ROMO originally anticipated.

The fact, that improving dynamic yaw misalignment with iSpin Yaw is of significantly less market value than expected, put a lot of cost pressure on iSpin Yaw if mainly used for automatic static yaw misalignment correction. We still believe in a market for iSpin Yaw for automatic correction of static yaw misalignments - which is a significant market problem – but this observation together with very promising power curve measurement results obtained from Nørrekær Enge (please see results section below) made us prioritize the performance and power curve monitoring market opportunity for iSpin.

The iSpin Yaw software was developed during H2 2015 but we decided to delay the testing and implementation as otherwise originally planned and rather focus on developing the data management solution for performance measurement and to focus on documenting power curve measurement with iSpin in compliance with the IEC 61400-12-2 standard.

For the above reasons and other market observations, it became clear that the iSpin Brain solution developed by Mita-Teknik was far too expensive for the market. ROMO would have to significantly further reduce the iSpin hardware cost in order for iSpin Yaw to become sufficiently commercially attractive. In this period we also got clear customer feedback that ROMO as part of correcting yaw misalignment with an iSpin Yaw Kit also has to directly document the extra power by correcting the yaw misalignment involved, and that customers are indeed very interested in having equipment on their turbines that constantly report how the turbine power curve performs.

Many of the iSpin Brain components delivered by Mita-Teknik were not tailor made for the need for the iSpin product or service, which made the overall solution they provide far too expensive. After careful analysis of the hardware needs, ROMO therefore decided to start developing a highly cost effective tailor made iSpin solution in collaboration with Prevas A/S. At the same time we decided to deposit all electronics components in the Spinner except for equipment necessary for iSpin Yaw. The new highly optimised and versatile solution also suited for installation in new wind turbines was (code) named iSpin X.

We therefore in this period began to put significant efforts in further documenting the iSpin technology for performance measurement and monitoring as well as on further reducing the iSpin equipment cost as well as to complete database development and software for automatic analysis, reporting and handling the much larger amount of data produced when monitoring wind turbines. ROMO therefore in April 2015 applied EUDP for an ultimate and final project extension, which was accepted by EUDP until end of 2016.

4.4 Project period from H2 2015 - H1 2016

The electronic iSpin Yaw software development was completed in this period and installed on a Siemens 2.3 MW wind turbine in the Nørrekær Enge wind farm. It will be tested in the second half of 2016 until project completion. This will be a major project focus for the remaining project period. In addition, ROMO will complete the development of iSpin X and make it ready for large-scale manufacturing and rollout.

5. Project results and dissemination of results

In accordance with the project plan the results are separated into technical development results and data demonstration results.

5.1 Technical iSpin development results

5.1.1 iSpin X

When ROMO Wind decided to initiate the development of iSpin X, our main goals were to design a system that was both flexible and cost effective enough to support ROMO Wind's growth for many years to come. The iSpin X hardware can be configured in several ways depending on the application for which it will be used. The hardware is based on two separate parts 1) the iSpin X main board which is the controller and processing unit and 2) the iSpin X I/O board which is the input / output expansion unit that will be used for iSpin Yaw (and other future) applications.
The iSpin X mainboard is based on a dual core ARM9 processor with one GB RAM and 16 GB Flash storage. Furthermore the mainboard has built-in 3G GSM modem and Wi-Fi for wireless communication with the outside world. The mainboard is also equipped with Ethernet, USB, CAN and RS422 communication ports for communication with e.g. the wind turbine controller. The iSpin X platform uses a real time Linux operating system. See also the preliminary iSpin v3.0 datasheet.

The iSpin X I/O board is, an expansion board mainly designed for iSpin Yaw. The board have eight analogue inputs, four analogue inputs, 16 digital inputs, 16 digital outputs and five RS232/RS484/RS422 serial communication ports.

Generally the iSpin X platform is designed to meet the harsh requirements known in the wind turbine industry mainly being long life time 20 years, extended temperature operating range -30 °C to 60 °C, durability towards vibrations, bump, shock EMC and lightning.

The iSpin X platform development project started in H2 2015 and was almost completed in H1 2016. The remaining parts of the development project are to finalize documentation and production test equipment. During H2 2016 ROMO Wind will run a significant amount of field test to verify that everything that has been tested in the lab also works in a wind turbine. We expect to start producing iSpin products based on iSpin X towards the end of 2016.

5.1.2 iSpin Yaw

iSpin Yaw searches to reduce the dynamic yaw misalignment to a minimum by means of the iSpin technology measuring the wind in front of the rotor. The conceptual idea of iSpin Yaw is basically to trick the wind turbine controller in to believing that the wind is coming from a different angle than its own wind directions sensors are telling it. In order to do that iSpin Yaw must know the wind direction according to the wind turbine's own wind direction sensors and also the wind direction according to the iSpin system located in the wind turbine's hub. Therefore the turbine's wind direction sensors must be feed through the iSpin Yaw system and into the wind turbine controller. At the same time iSpin Yaw receives wind signals from the iSpin system in the hub via wireless transmission. This is shown in the principal diagram in Figure 6.

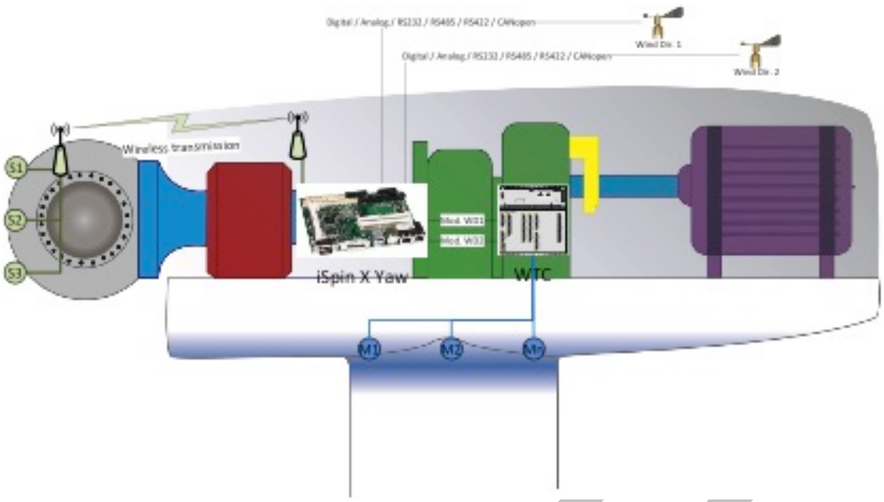

Figure 6: The iSpin Yaw principle.

In order for iSpin Yaw to trick the wind turbine controller to read corrected wind direction signals, iSpin Yaw has been designed according to some very high performance criteria, because if the wind turbine controller doesn't receive the expected signal or sees the expected change in the signal with a certain frequency it will shut down the wind turbine.

iSpin Yaw has been designed to have a maximum turn around delay of 10ms. Meaning that maximum 10ms after a signal change is read on the input the same or a corrected value must be available on the output. Further in order to avoid that the wind turbine shuts down due to missing wind direction signals iSpin Yaw has been designed with a failsafe option which maximum 20ms after detecting a malfunction or fault electrically routes the wind direction signals directly in to the wind turbine controller.

As mentioned earlier iSpin Yaw has a large number of different inputs and outputs. Not nearly all of them are needed in every application, but because wind turbines have different combinations of wind direction sensors iSpin Yaw must be prepared for all kinds of applications. These many different combinations of wind directions sensors are obviously difficult to know beforehand. Therefore for unknown wind turbines types iSpin Yaw has the possibility to listen to the wind direction signals while just feeding them directly through to the wind turbine controller. During this period of "listening" extensive data logging and storing of all signal levels take place. ROMO Wind's software engineers then collect the logged data for further analysis. After extensive analysis of the signals the software engineer will make an application program that works with this specific turbine type.

Together with Mita-Teknik ROMO Wind has developed the first iSpin Yaw prototype system for a Siemens 2.3 MW. The algorithms from this development will be transferred to iSpin X Yaw during H2 2016. Further during H2, 2016 we intent to develop another application for either a Vestas V80 or a Senvion MM92 depending on turbine availability. In order to document the effect of iSpin Yaw for each turbine type ROMO Wind must first establish a baseline power curve, then activate the iSpin Yaw application and then finally make a verification power curve.

5.1.3 Data management and reporting system

With the change from running measurement campaigns towards permanent monitoring the need for a smart datacentre became apparent, as the need for reporting would grow rapidly with each added turbine to be monitored.

The goal was to design a scalable data management and reporting system, i.e. a data centre, which is able to support automatic reporting and monitoring of wind turbines, where iSpin systems are installed. As an initial benchmark concerning the performance of the data centre it should allow to handle 2000 wind turbines with the current work force of four people in the analysis and reporting department. The data centre should be capable to tell when a wind turbine in the field observed a change in static yaw misalignment, and - in future - when a change in power performance characteristic of a wind turbine occurred.
With the amount of individual turbines to be continuously monitored, it was necessary to set up a smart system, capable of self-diagnosis and automatically warning respectively alerting when a problem of a iSpin system should occurr. For the task we selected a local programming company SCADA Minds, to assist us in developing such a system.

Today the data centre is operational and daily assists ROMO Wind in monitoring the entire fleet of turbines, where iSpin is operational. The data centre has a dashboard alerting us when changes are observed on individual turbines. Status reports are automatically generated from here and the system allows keeping tractability in all documentation shared to clients. On demand measurement data can be extracted and shared with clients. External data, i.e. time synchronised SCADA data, can be imported for performance evaluation.

The data centre has been so successful that it now supports across all functions at ROMO Wind:

- Sales handover documentation to project can be imported and used to generate new projects automatically in the system.
- Sales can use the system to get an overview of the projects their status and current conditions and observations at any location.
- ROMO Wind’s service team can export work orders from the system when technicians need to adjust a wind turbine or service a system.
- Data analysis group can dig deep into the data and make individual investigations and studies whenever the systems report an alert. If a new yaw misalignment has been observed for a turbine it is possible - within seconds – to generate wind climate reports for the individual turbine for any given selected time period to understand if a change is caused by climate or something turbine specific might have caused the changed behaviour of the wind turbine. Most importantly, the new database allows ROMO Wind to perform advanced data mining on individual turbine types, across all projects, clients or cross correlation investigation on multiple turbines.

5.2 Data demonstration results

5.2.1 Demonstration of iSpin wind measurement compared to other technologies

Wind measurement capabilities of iSpin were directly compared to three other commonly used wind measurement technologies in the market: The met-mast; a nacelle lidar, and the wind turbine’s own nacelle anemometer. This was demonstrated in the Vattenfall owned, Nørrekær Enge wind farm. The results were and are still being distributed in a report that ROMO is now routinely and widely using in it is sales and marketing efforts[6].

[6] *The iSpin technology compared to other wind turbine wind measurement technologies. ROMO Wind report. 16 July. 2015.*

The study was conducted on a single Siemens 2.3 MW wind turbine located in flat, non-complex terrain. The wind farm contains a total of 13 of these turbines arranged in a single row facing northwest. The wind farm layout is illustrated in the figure below. The measurement campaign comprised the collection and analysis of time synchronised wind measurement data from a met-mast placed in front of turbine no. 4, from a nacelle lidar and from the ROMO Wind iSpin equipment also installed at this turbine. In addition, the turbine power production, the nacelle direction, and the site air temperature and pressure were recorded, as well as the wind measurement data from the wind turbine's nacelle anemometer. Data was collected in parallel over the entire measurement period from January to May 2015. The wind farm lay-out is illustrated in Figure 7.

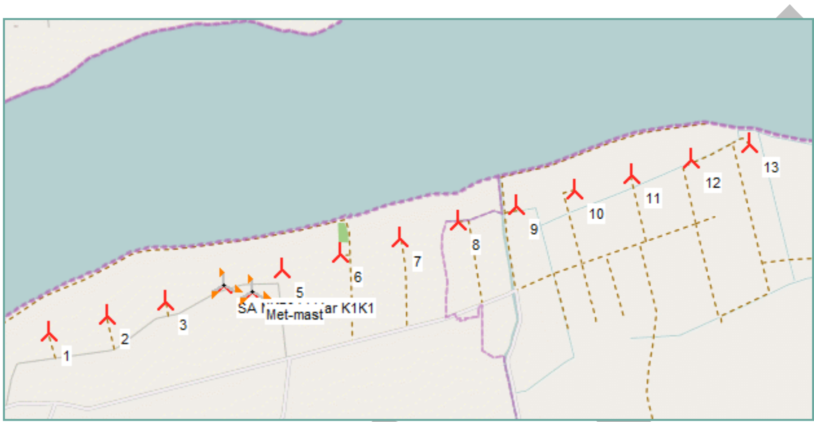

Figure 7: The design of the Vattenfall-owned Nørrekær Enge Wind farm. 13 pcs. Siemens 2.3MW.

Yaw misalignment measurement

ROMO Wind iSpin technology operates with two different yaw misalignments types: The static (or average) and the dynamic yaw misalignment (the variation around the static misalignment). This is illustrated in Figure 8

A wind turbine today is for technical/practical reasons not able to accurately follow the constantly changing wind direction by instantly adapting its nacelle direction directly towards the wind. The turbine manufacturers therefore use different types of yaw motors, yaw systems, power and load measurements to realise their yaw control algorithm strategies. These choices along with the quality of the incoming wind direction signal from the nacelle wind direction sensors determine the quality of the turbine yawing, and the extent of turbine yaw misalignment. Some dynamic yaw misalignment is always to be expected although ROMO Wind has observed wide variation among different wind turbine types and brands in the market. Wind turbines should generally always have approximately zero degree static yaw misalignment, although this is also not the case in most wind turbines according to ROMO Wind's observations.

The following graphs show a direct comparison of the measured yaw misalignment using an IEC compliant met-mast as well as the nacelle lidar and the iSpin equipment. The met-mast was used as the yaw misalignment validation reference by determining the wind direction and comparing it to a simultaneous direction measurement of the wind turbine nacelle. The difference between the real wind direction and the nacelle direction is defined as the yaw misalignment.

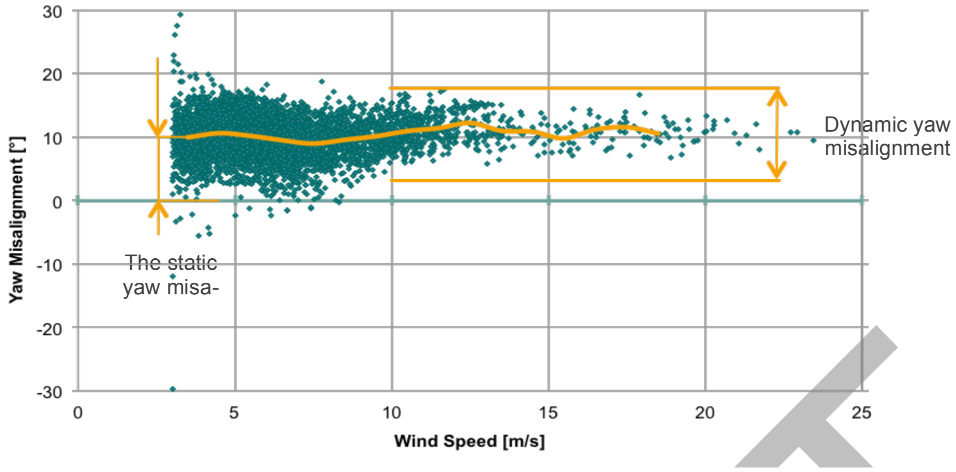

Figure 8. The two types of yaw misalignment: Static and dynamic.

Below the data filtered from measurements from the free wind direction only is shown. These data are not affected by wake conditions or obstacles distorting the wind flow towards the turbine, which makes it possible to directly compare the yaw misalignment from the met-mast, from the nacelle lidar and from the iSpin system. Furthermore this filtering was applied to exclude data when the nacelle lidar is in half wake conditions or when the met-mast is in wake though the turbines are not. Following this approach all the yaw misalignment data from the three types of equipment is directly comparable.

Figure 9 shows wind direction data from the met-mast (x-axis) and the direction of the nacelle (y-axis).

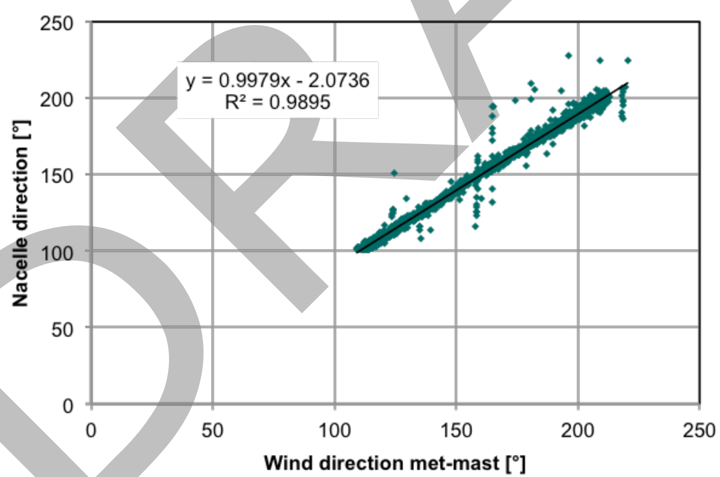

Figure 9. Measured nacelle direction versus wind direction from the met-mast

The figure illustrates the yawing performance of the wind turbine and how accurately the wind turbine can be controlled by the use of its wind direction sensors. On average there is about +/- 6 degrees dynamic yaw misalignment of the turbine. As previously mentioned this is driven by the turbine yaw control, which can never be better than the quality of the wind direction provided by the nacelle wind direction sensor. Moreover there is a static yaw misalignment of about 2 degrees visible between the direction of the nacelle and the real wind direction measured by the met-mast.

Figure 10 shows the wind direction determined by the met-mast (x-axis) is plotted versus the wind direction determined by the iSpin sensors (y-axis).

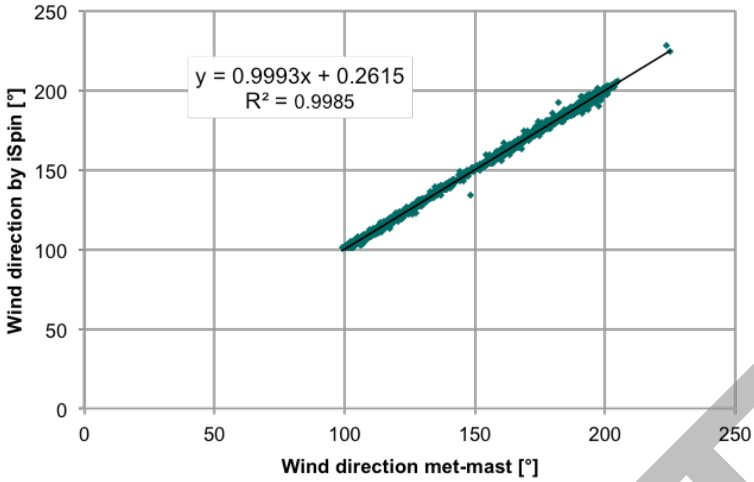

Figure 10. Measured wind direction by the spinner anemometer versus the wind direction of the met-mast

The iSpin system wind direction was calculated by addition of the measured yaw misalignment angle to the measured nacelle direction angle. It is evident that yaw misalignment measured by the iSpin system is more precise as the scatter is much less than with the met-mast measurements. Furthermore the offset is also eliminated because the spinner anemometer, due to its measurement principle, has no offset. This confirms the high yaw misalignment measurement capability of the iSpin technology.

It should be noted that due to real site conditions it will never be possible to get a perfect 1 to 1 ratio between the wind direction observed with the iSpin system and the met-mast, respectively - although it is here very close. This would only be obtainable in a wind tunnel under controlled wind conditions, as natural fluctuations and small changes in wind direction will always cause scatter between two measurements points in a 3-dimensional world under outside turbulent wind conditions. Compared to the nacelle wind direction sensor however, it seems to be possible to improve the turbine yawing performance (dynamic yaw misalignment) by a factor of 2 (two) if the iSpin system data would have been used by the turbine control system. Furthermore, this would also mean immediate and automatic correction of any static yaw misalignment.

The actual yaw misalignment detected by the iSpin sensors over the range of wind speeds is shown in In Figure 11 it is obvious that the dynamic yaw misalignment is more pronounced at low wind speeds. Also the yaw algorithm could be improved as function of wind speeds, to average out the static yaw misalignment for all wind speed ranges.

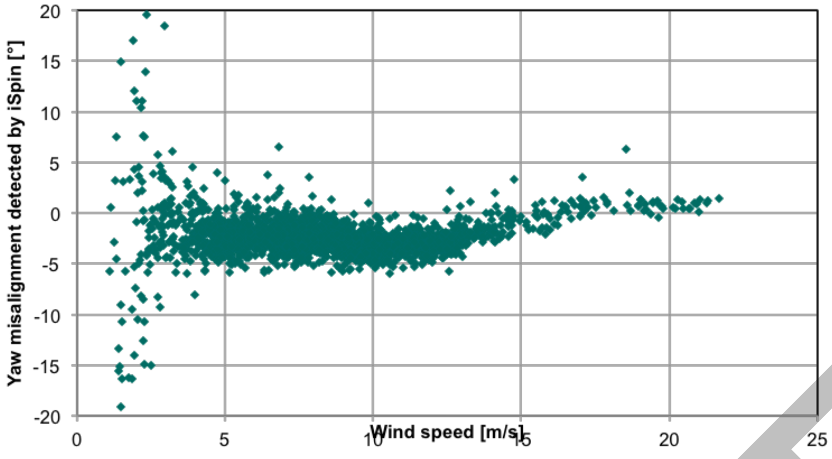

Figure 11. Measured 10 min average yaw misalignments based on Spinner anemometer as function of the wind speed

Figure 12 below illustrates the same data comparison with the met-mast wind direction, but now using the nacelle lidar as the measurement device for yaw misalignment detection. It is immediately clear that this system produces much more variation in the yaw misalignment measurements. The nacelle lidar shows a significantly higher scatter than both the iSpin sensors and even the real nacelle direction alone. This is likely to be a result of the large measurement volumes of the lidar beams in non-correlated wind fields.

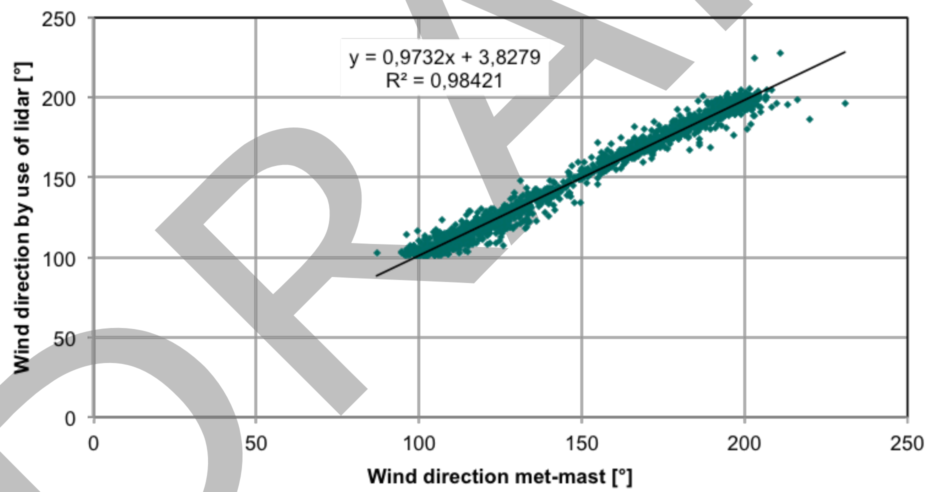

Figure 12. Wind direction using lidar as input for yaw misalignment measurements versus wind direction of the met-mast

Figure 13 below illustrates the measured yaw misalignment with the nacelle lidar versus the wind speed. Once again the nacelle lidar shows much higher deviation from the average yaw misalignment. Both systems measure roughly the same static yaw misalignment, but the nacelle lidar shows significantly higher dynamic yaw misalignment than the spinner anemometer.

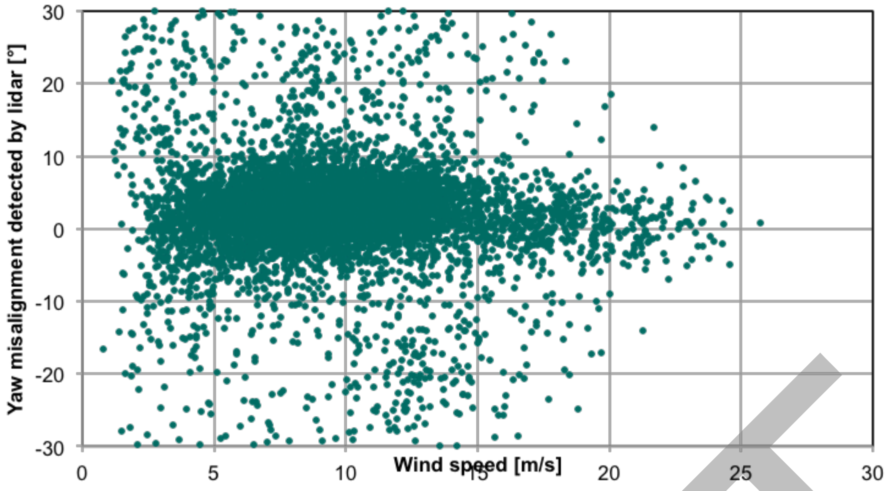

Figure 13. Lidar measured yaw misalignment as function of wind speed

Figure 14 shows the measurement variation of the nacelle lidar (orange) and the iSpin system (green). It can be clearly seen how much the nacelle lidar can "spike out" compared to the iSpin technology. Where the nacelle lidar data can vary from +15 degrees to -15 degrees or more within 10 minutes, the iSpin system measurement is significantly more stable as validated by comparing to the wind direction measured by the met-mast.

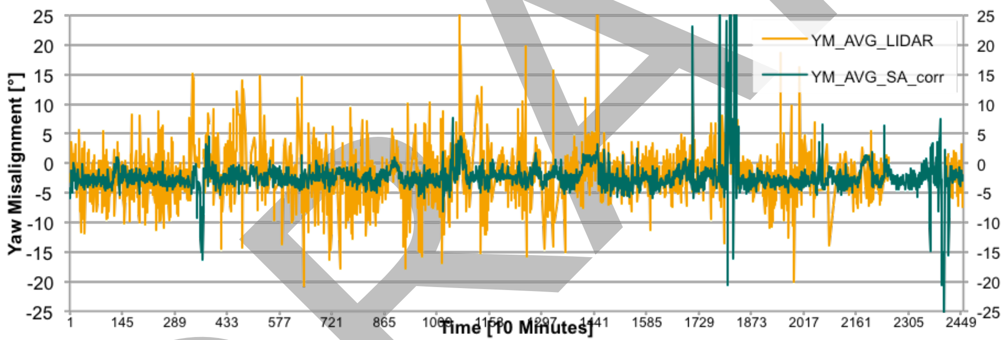

Figure 14. Direct comparison of measured 10 min average yaw misalignment for Spinner anemometer and lidar

It should be emphasised again that the above data was only collected from the undisturbed wind sector of the wind turbine. A comparison of the measured yaw misalignments 360 degrees around the turbine from the nacelle lidar as well as the iSpin system versus real wind direction obtained by the met-mast is shown in Figure 15.

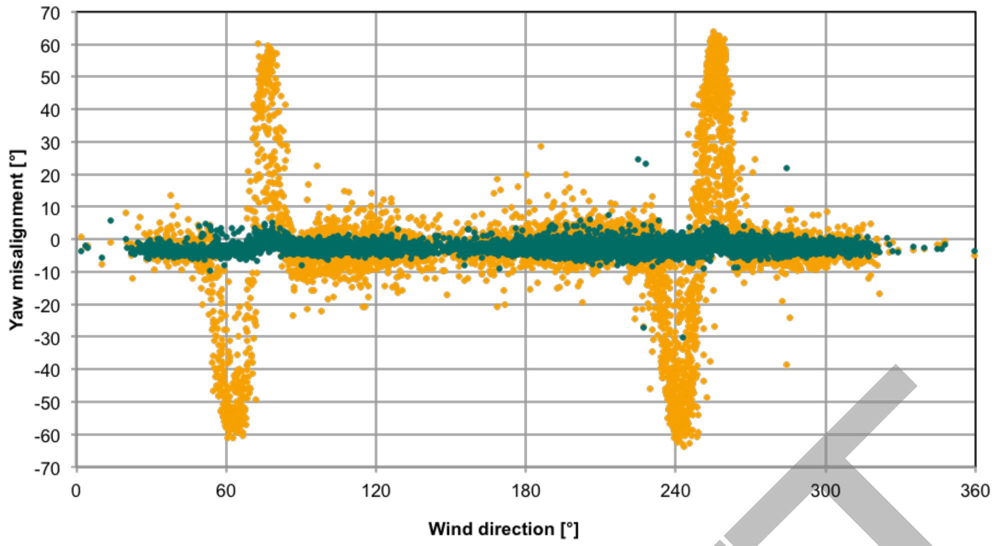

Figure 15. Measured yaw misalignments when measuring in all wind sectors. Nacelle lidar (orange) and iSpin (green)

It is obvious that the nacelle lidar in some sectors is measuring the yaw misalignment in half wake from the other wind turbines. This fact does severely impact its measurement ability.

Because of the wind farm layout (see Figure 7), the nacelle lidar measures up to +/- 60 degrees yaw misalignments, caused by wakes from the neighbouring wind turbines. As mentioned before this is driven by one of the lidar beams is measuring in the wake zone while the other beam is measuring in free wind. This causes incorrect results for yaw misalignment from the lidar. In contrast, the iSpin system is unaffected by the wake phenomenon and shows a perfect relationship with the wind direction from the met-mast.

Power curve measurement

In the following section the nacelle anemometer, the nacelle lidar and the iSpin sensors are directly compared to the wind measurements from the met-mast. Importantly, once more only data recorded from the undisturbed wind direction sector is shown.

The spinner anemometer as well as the nacelle anemometer is, in contrast to the nacelle lidar, included in the IEC 61400-12-2 standard for measurement of wind turbine power curves. For the iSpin a calibration clarification sheet as a supplement to the IEC-standard, was accepted and subsequently published by the IEC committee in November 2015[7]. The iSpin sensors in this study were calibrated according to this procedure.

In Figure 16 (left panel) it can be found that the Nacelle Transfer Function (NTF) for the nacelle anemometer is not 100% representative for the met-mast wind speed concerning the wind conditions on this site, even though the wind farm is located in a very flat, non-complex terrain. The nacelle anemometer measures on average 6.2% higher wind speed than the actual wind in front of the turbine according to the ratio to the met-mast. Furthermore and importantly it is non-linearly related to the actual wind speed.

[7] Use of spinner anemometers. CSH001, IECRE, November 2015.

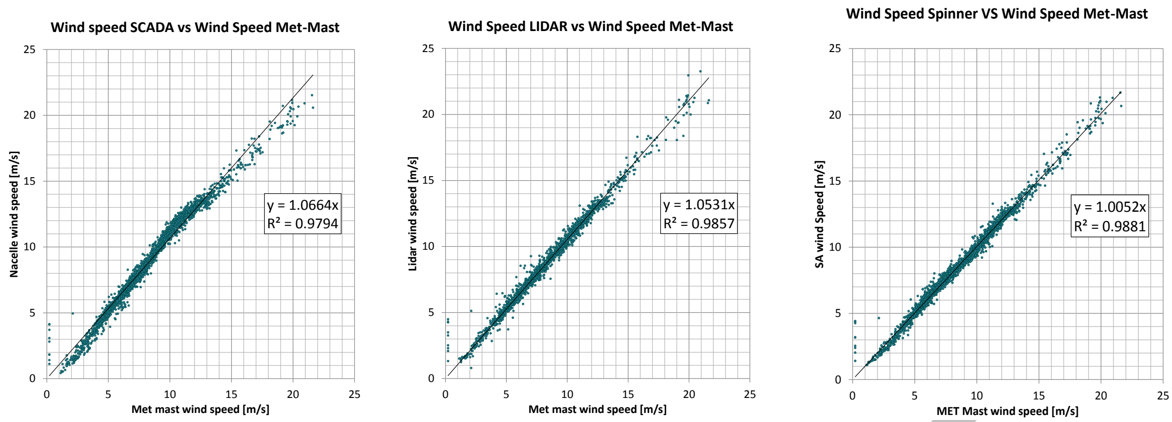

Figure 16: Nacelle anemometer (left), nacelle lidar (mid) and iSpin (right) versus met-mast wind speeds

The nacelle lidar in this study measured wind speed with quite high correlation to the met-mast and a linear response, but on average it measured 5.5% higher wind speed than the met-mast. ROMO later found out that the nacelle lidar manufacturer made a software mistake, when servicing the lidar, and which was causing this error.

The iSpin system showed better correlation to the met-mast wind speed than the nacelle anemometer as well as the nacelle lidar. This iSpin measurements have been calibrated by use of the the met-mast to deriving a transfer function which transforms the iSpin sensor measurements into free wind speed measurements. The corresponding power curves for *the free, open* wind sector are shown in Figure 17.

When evaluating the nacelle anemometer, lidar and met-mast power curves it is observed that the measured power varies significantly compared to the iSpin measured power curve. The met-mast measurement produces a similar power curve as the nacelle lidar, but with slightly lower average wind speeds due to the above mentioned software error. The observed variation is caused by natural turbulence and variation in wind speed as the wind moves from the met-mast to the turbine. Over this distance the wind speed can change slightly and also to some extent change direction - worse in complex terrain than in flat terrain.

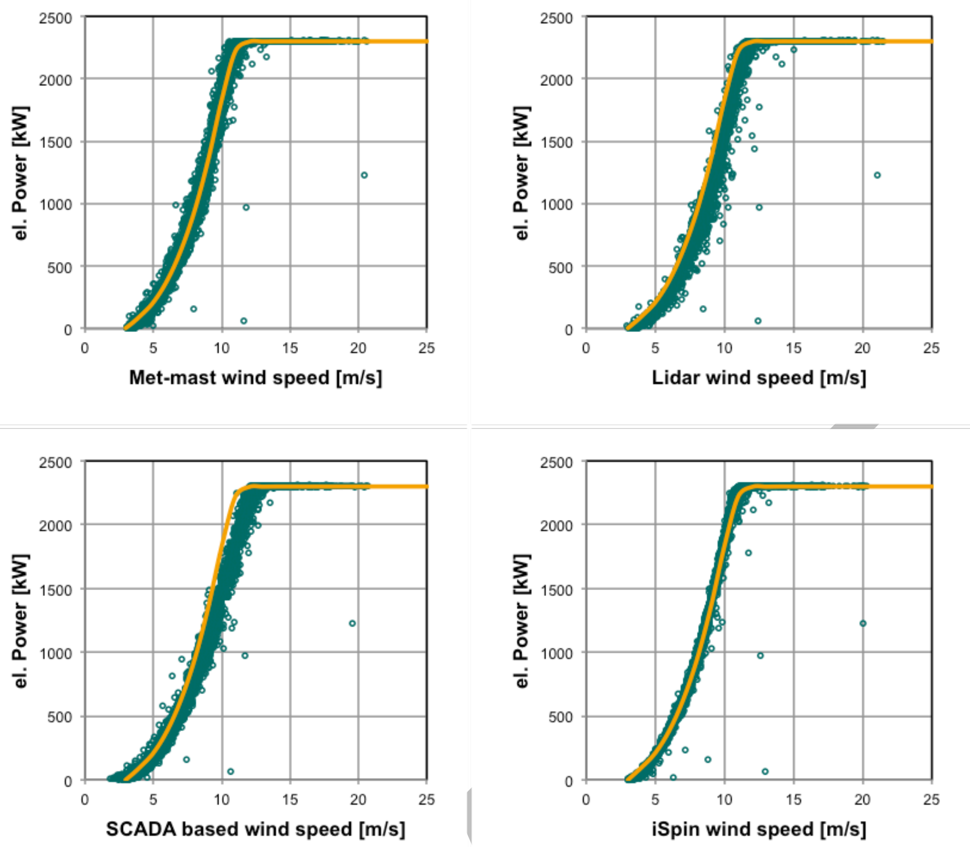

Figure 17: From the top left: Power curve measured by: met-mast, Lidar, nacelle anemometer, and iSpin (all green), respectively, relative to the OEM warranted power curve (orange)

When measuring the power curve using the iSpin sensors it is obvious when,comparing to the other measurement technologies, that the iSpin system measures the power curve with significantly lower scatter. The variability is, around only 2/3 of the industry standard met-mast. This is caused by the fact that the iSpin sensors measure the actual wind hitting the rotor and not the wind conditions 2.5 rotor diameters in front of the wind turbine as measured by the met-mast and nacelle lidar. The standard deviations for the different power curves are compared in Figure 18.

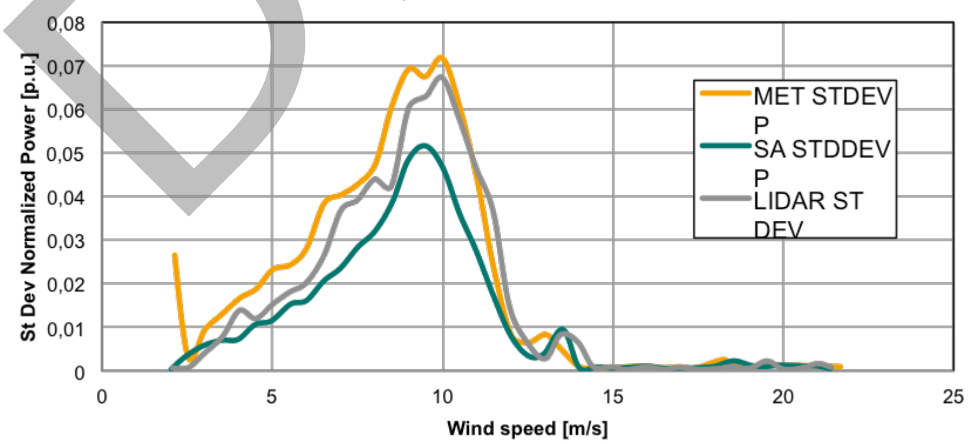

Figure 18. Comparison of standard deviation of power variations at different wind speeds from the met-mast (orange), nacelle lidar (grey), and the iSpin sensors (green)

The energy in the wind is proportional to the cube of the wind speed, so a 2% error on the wind speed measurement will result in an 8% power curve error. The wind speeds measured by the iSpin system yield the absolute lowest scatter on the measured power curves – even when compared to the met-mast, which also means a significantly lower error on the power curve.

It should be emphasised again that all the above power curves shown in Figure 17 were recorded exclusively from the undisturbed wind sector of the wind turbine No. 4. During the data analysis, data sets from other wind direction sectors were filtered out.

However, it is highly relevant to examine how and to what extent turbulent wind conditions in wakes do affect the monitoring capabilities of the different wind sensing systems, especially when it comes to turbine control, but also in the daily monitoring and operation of wind turbines.

As already illustrated in Figure 13 and Figure 14 above, the nacelle lidar experience significant problems in general, when measuring yaw misalignment and not least when in wake by other turbines (Figure 15) or due to other flow disturbances on the site. The met mast measurements in general are of course disturbed, when the mast is standing in wake of wind turbines. Data from a met-mast is only useful - and relevant - when both the met mast and the turbine are pointing towards free wind sectors.

In Figure 19 power curves are shown based on the met-mast, the nacelle anemometer, the nacelle lidar and the iSpin. In contrast to Figure 17 these curves shows the result when measuring the wind from *all wind sectors*. The curves thus now also include situations where the turbine and its measurement systems, as well as the met-mast, stand in wake of other turbines.

The met-mast is obviously not following the yawing of the wind turbine so the comparison in Figure 19 only illustrates the already known influence of wake and turbulence on met-mast measurements and why the IEC 61400-12-1 standard for performance measurement using a met-mast strictly requires filtering of the data to only include data when measuring the free wind turbine sector.

Interestingly, the nacelle anemometer power curve (top left panel) from this completely flat and very simple site is influenced significantly. This problem, which makes the nacelle anemometer useless for performance monitoring, is also well known by the industry. The variation is caused by even small changes in wake turbulence and inflow angle changes occurring, when the wind is coming onto the turbine downstream from a neighbouring wind turbine. Such wind conditions severely influences the nacelle transfer function (NTF) developed by the turbine manufacturer aiming at mimicking the free wind, and it indicates that the turbine NTF is only to some extent reliable under completely undisturbed wind conditions.

The observed huge scatter on the power curve measured with the nacelle lidar (bottom left panel) is a direct result of the lidar measuring in the wake of the neighbouring wind turbines. It is thus very likely that at several times one of the lidar beams is measuring the free wind speed, and another of the lidar beams is measuring in the wake. At other times both beams will be in free wind while the turbine rotor will be in wake conditions. As illustrated for yaw misalignment measurement in Figure 15, the nacelle lidar also for free wind speed measurements seem to constitute a substitute for a met-mast. The nacelle lidar is also only reliable in the free wind sectors of wind turbines.

Importantly, in contrast to all the other technologies the iSpin technology seems not to be affected by the wakes and different flow conditions hitting the wind turbine on the site (bottom right) i.e. The iSpin seems to be site-independent. The turbine specific NTF obtained during calibration of the iSpin sensors may thus be valid stable in all site and terrain conditions, like free wind flow, wakes, wind coming in over land or from the stretch of sea which is directly north of the wind farm. This characteristic, being uniquely provided by the iSpin technology is a very important capability when it comes to turbine performance monitoring and control of entire wind farms. However, the validity of this hypothesis needs signficantly further field proof by using iSpin for testing on more wind turbine types and in wind farms located in different terrain classes (semi-complex, complex, offshore)

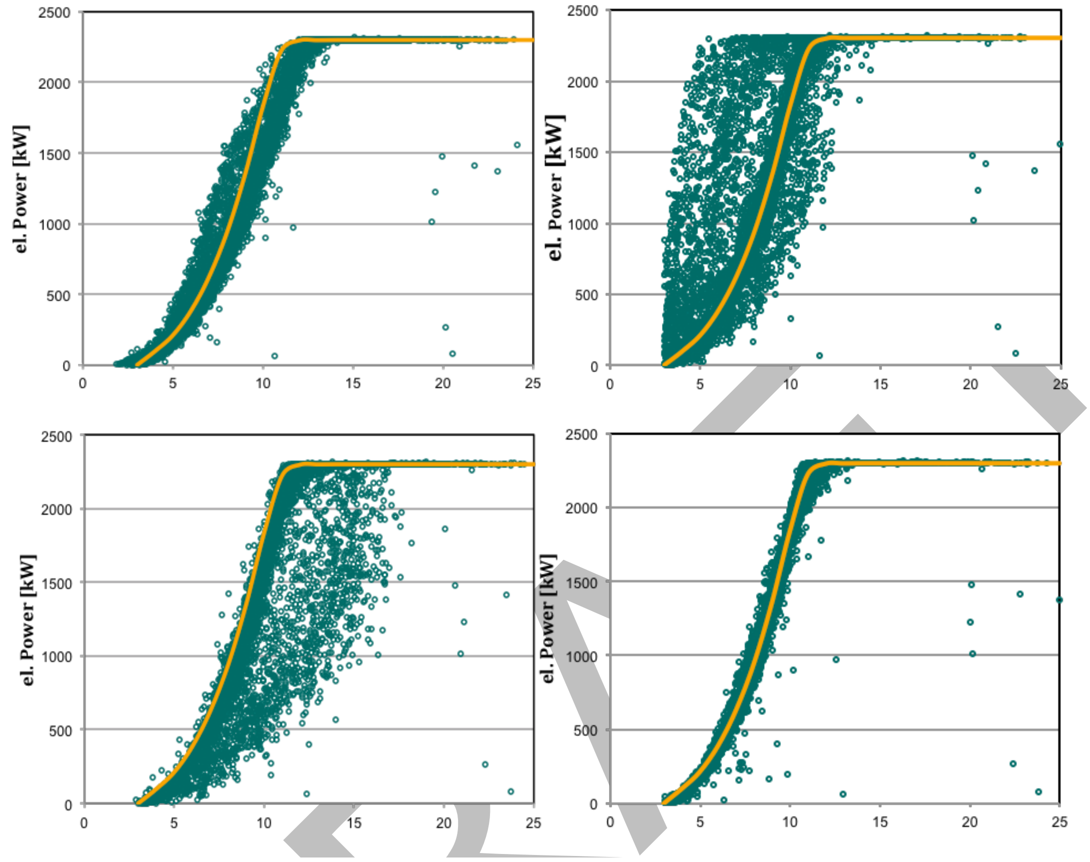

Figure 19. Power curves recorded from the nacelle anemometer (upper left), the met-mast (upper right), the nacelle LiDAR (lower left) and the iSpin (lower right) measuring the wind 360-degrees around the turbine, relative to the warranted Power curve (orange)

The establishment of this unique property of iSpin was the reason why ROMO and DTU Wind Energy in April 2016 decided to re-apply EUDP for a new grant enabling a field demonstration of this property. The prospect for the wind industry in general that iSpin could serve as a universal tool for verifying and monitoring turbine performance over their entire lifetime - which has not so far been possible despite huge investments in the sector – is indeed very promising. This is further illustrated below.

5.2.2 The iSpin Guardian approach

What does it mean to use iSpin measurement data to generate power curves and get an idea about the performance of each individual turbine or a complete wind farm? Figure 20 is showing the power curves using 360° inflow and being measured with the iSpin system and the nacelle anemometry, i.e. provided by the turbine SCADA systems for the Nørrekær Enge wind farm located in Denmark. In addition to this, power curves the IEC 61400-12-1 compliant power curve - measured with a met mast in front of turbine number 4 - is also shown. For this evaluation 9 of the wind farm turbines have been used (T2 to T6 and T10 to T13) (de-rated turbines were excluded).

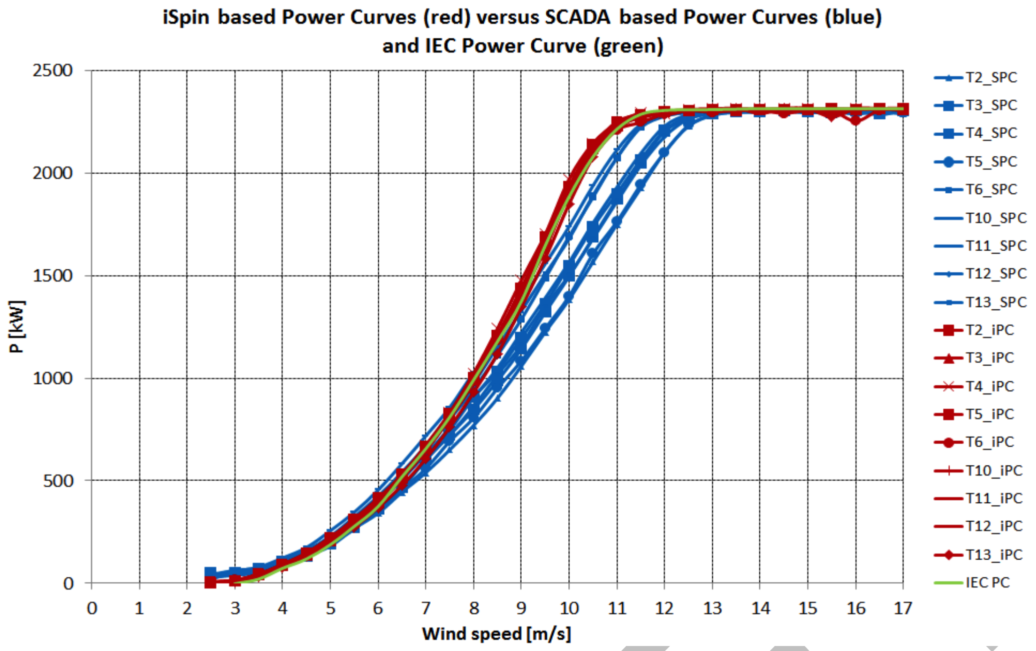

Figure 20. Comparison of power curves based on iSpin and nacelle anemometer measurements

From Figure 20 several important conclusions can be made:

- SCADA power curves are useless for wind park operation. All these 9 wind turbines except for one turbine having a yaw misalignment are operating correctly. However, this is certainly not reflected by the nacelle anemometer power curves reported from the wind turbine's SCADA system. None of the SCADA power curves match the IEC and OEM warranted power curve and apparently all 9, wind turbines underperform if the SCADA power curves were taken seriously.

- Not only is the average SCADA power curve reported by nacelle anemometers wrong, a very large variation between the different turbines can be seen. This variation corresponds to +/- 8% variation in AEP. The operator could thus have spent a lot of time and money trying to "repair" well performing wind turbines.

- The nacelle anemometer calibration factors as well as the nacelle anemometry NTFs, which were established by the OEM for this particular wind turbine turbine type, are no longer applicable or usable for 360° inflow, which is the reality of daily wind park operation and monitoring.

- In contrast to the SCADA power curves all nine iSpin power curves based on 360° measurements match the IEC power curve very well. The average difference between the 360° iSpin power curves and the IEC power curve was only 0.7%.

- All iSpin power curves vary within only 2.1% in AEP. If correcting turbine no 13 having a 6.8-degree yaw misalignment they would vary less than 1.1%.

A study by DTU concerning iSpin based power curve measurements according IEC 61400-12-2 at turbines within a wind farm has just been finalized. This study is part of a PhD work and aims for the evaluation of the resulting power curves and annual energy production of different wind farm turbines with special focus on the uncertainty components and the overall AEP uncertainties[8]. A result showed that transfer of the measured NTF from one wind turbine to a neighbouring wind turbine showed an AEP difference of only 0.38%.

It is thus obvious from this study that using SCADA based power curves makes it today literally impossible to identify and intervene against underperforming wind turbines in a wind farm. The recorded SCADA power curves in terms of AEP variation varied +/-8% (red band in Figure 21) and on average they are not even close to the warranted turbine power curve for a Siemens 2.3 MW turbine.

In contrast, iSpin –even when recording power curves on all turbines in wake of other turbines– accurately describes the performance of all 9 wind turbines with a more than 7 times lower variation than the SCADA power curves (green band in Figure 21) and in full accordance with less than 1% of the OEM warranted power curve. In contrast to the nacelle anemometer NTF, the iSpin NTF is fully stable and transferable between wind turbines irrespectively of local wind conditions. Although the very low power curve variation obtained for iSpin may increase somewhat if measured over an entire year due to seasonal variations, similar increase in variation would also be seen for the the SCADA power curves.

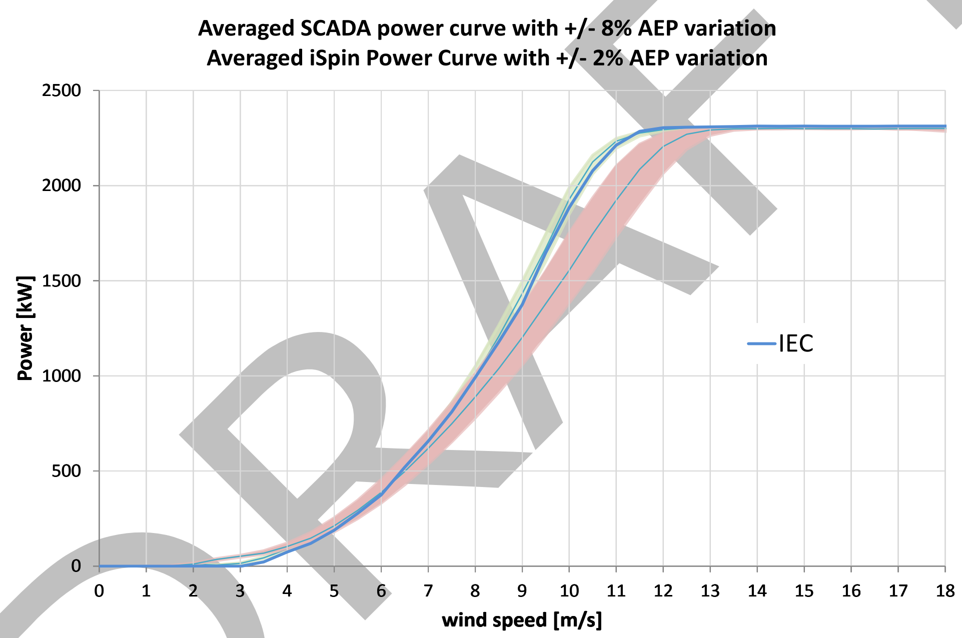

Figure 21: AEP variation bands found at NKE test site for iSpin based PCs (green) and SCADA based PCs (red). Not only is the variation for the SCADA power curves significantly higher than for iSpin, the average is also directly wrong and not overlapping with the manufacturers warranted power curve.

This makes iSpin a unique monitoring tool, which so far has not been available in the wind power industry. Furthermore, the low maintenance need and cost of iSpin enables it use for permanent monitoring of wind farm performance of the entire wind park lifetime. This has also not been possible. ROMO Wind names this principle “iSpin Guardian”.

[8] Wind turbine power performance measurement with the use of spinner anemometry, DTU Wind Energy PhD-0063(EN), August 2016, Giorgio Demurtas

An example of using the iSpin Guardian principle for identifying and underperforming wind is turbine no 13. This turbine had a 6.8° yaw misalignment detected by iSpin, whereas the other turbines only showed insignificant yaw misalignment. Consequently the power curve and corresponding AEP of turbine no 13 differs from the power curve compared to the turbines without yaw misalignment (see orange line in Figure 22 below).

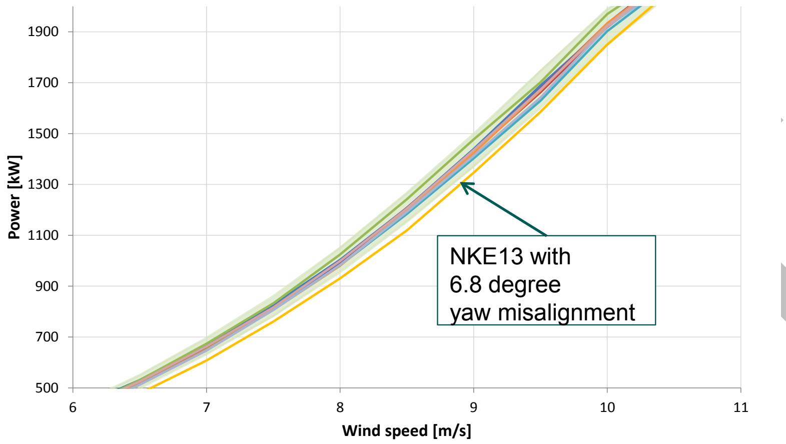

Figure 22: Identification of a turbine outside normal operation

The Nørrekær Enge field experiment demonstrates for a flat terrain site that it is possible to apply the iSpin wind speed measurements and iSpin Guardian principle to generate a reference turbine performance characteristic including a band for the wind farm and to compare the other turbines in the wind farm to this reference.

To transfer the iSpin Guardian monitoring approach to other wind farms, iSpin systems should be installed on all turbines in the wind farm. Only one of the wind turbines would need an IEC compliant power curve reference measurement, which also serves to generate the iSpin free wind speed calibration factor and NTF. Preferably after commissioning an accredited 3rd party consultant should perform power curve verifications according IEC 61400-12-1 and 12-2 on one wind turbine in the wind farm, using an IEC compliant met-mast set-up and calibrated iSpin equipment. After some plausibility checks the free flow calibration factor and NTF derived at this reference turbine can then be applied to all the other turbines to measure the wind and accurate power curves for comparison to the reference turbine can be recorded. In the future monitoring of the wind farm iSpin Guardian will be able to help the operator to always secure optimal performance. This is exactly what we want to show in a larger field study described in a recent EUDP grant application.

Figure 23 shows a possible process flow to generate a site and turbine specific reference performance characteristic including tolerance band, i.e. perform the iSpin Guardian approach.

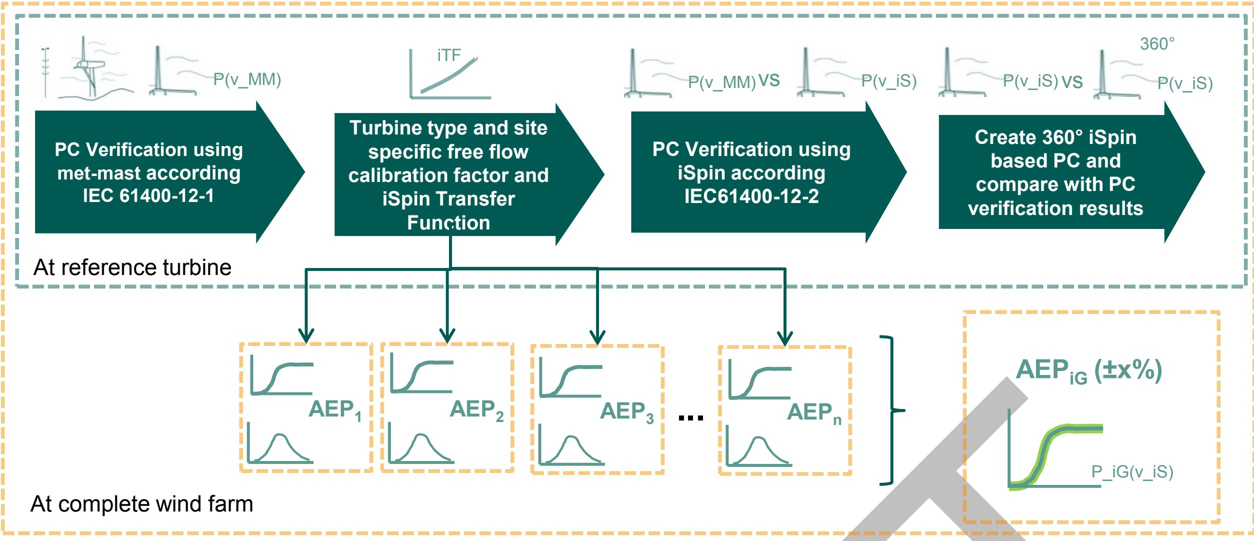

Figure 23: Possible process flow for iSpin Guardian approach

In order to achieve good results and low uncertainty in the generation of the AEP band, the requirements and data treatment listed in Table 1 should be fulfilled respectively performed when applying the iSpin Guardian approach. Although not essential, the best and most meaningful results will be achieved if the iSpin technology is factory fitted by the turbine manufacturer and directly connected to the turbine control system before delivery to the wind farm. This would allow the highest accuracy and repeatability of the sensor installation and the best timewise correlation with the turbine power signal.

Table 1: Requirements and data treatment for iSpin Guardian approach

Requirements	**Data treatment**
Turbine should have aerodynamic, rotationalsymmetrical spinner, because iSpin works under the assumption of well-defined flow on the surface of the spinner iSpin sensors to be installed with maximal tolerance of ±1.0cm Usage of wind tunnel calibrated iSpin sensors SCADA data to be used for creating power curve evaluations should be time synchronised to an internet time server with maximal ±3 seconds delay to time server.	Turbine must be operated below 2 degrees static yaw misalignment, i.e. yaw misalignment should be detected and corrected by use of iSpin in advance Different operation modes have to be treated with different reference characteristics Apply same data treatment on all measurements, i.e. at least: Air density correction to 1.225kg/m³ Turbulence intensity normalisation according to 61400-12-1 Ed. 2 (to 10%) Inflow normalisation to horizontal flow Shear and veer normalisation (if possible using iSpin measurements)

The iSpin Guardian approach is a scalable approach and therefore not limited only to the performance evaluation of a specific wind farm. After gathering reference measurements, i.e. free wind speed calibration factors and NTFs for a specific turbine type at several different sites, it should be possible to generate a turbine type specific performance characteristic which can be used for fleet wise evaluation of the turbine performance.

5.2.3 Uncertainties associated with measuring the wind turbine power curve using iSpin

The uncertainty analysis of spinner anemometer wind speed measurements is due to the integrated 3 sonic plus 3 accelerometer sensors and nonlinear conversion algorithm rather complex. To quantity the uncertainties DTU was asked to performed a study evaluating the uncertainty contributors and their effects on the wind speed and finally AEP uncertainty[9].

An overview of the uncertainty components being identified and evaluated can be found in Table 2, where the designation of each component follows IEC61400-12-2 as much as possible.

As a result of the study DTU proposed an uncertainty analysis method, which considers all potential influential parameters and derives uncertainty components that are relevant for the analysis. Due to the large variability of sonic sensor wind speed measurements and the accelerometer measurements during rotation a simulation model was developed which simulates the normal measurements of the spinner anemometer during operation of the wind turbine. A procedure for evaluation and expression of the uncertainty components on horizontal wind speed uncertainty was made.

Table 2: Sensitivity factors and correlation coefficients for uncertainty components related to spinner anemometer measurements according to IEC 61400-12-2

Uncertainty component	**Designation***	**Influence on**	**Sensitivity factors on U_{hor}**	**Correlation coefficients**
1. Calibrations • Wind tunnel calibration [m/s] • Angular calibration k_α [%] • Wind speed calibration k_1 [%]	$u_{N1,V1,i}, u_{N1,V2,i}, u_{N1,V3,i}$ u_{N41i} u_{N42i}	V_1, V_2, V_3 k_α k_1	$(\partial F/\partial V_1), (\partial F/\partial V_2), (\partial F/\partial V_3)$ $(\partial F/\partial k_\alpha)$ $(\partial F/\partial k_1)$	1,1,1 0 0
2. Operational characteristics • Inflow angle to rotor [º] • Turbulence [%] • Yaw misalignment [º] • Accelerometer vibrations [m/s^2] • Shaft tilt angle increase [º]	u_{N21i} u_{N22i} u_{N23i} u_{N24i} u_{N25i}	U_{hor} U_{hor} U_{hor} P_1, P_2, P_3 δ	1	0
3. Sonic sensor mounting • Longitudinal position [m] • Directional uncertainty [º] • Sonic path angle [º] • Lateral position [m] • Accelerometer alignment [º]	$u_{N31,V1,i}, u_{N31,V2,i}, u_{N31,V3,i}$ $u_{N32,V1,i}, u_{N32,V2,i}, u_{N32,V3,i}$ $u_{N33,V1,i}, u_{N33,V2,i}, u_{N33,V3,i}$ $u_{N34,V1,i}, u_{N34,V2,i}, u_{N34,V3,i}$ $u_{N35,V1,i}, u_{N35,V2,i}, u_{N35,V3,i}$	V_1, V_2, V_3 V_1, V_2, V_3 V_1, V_2, V_3 $V_1, V_2, V_3, P_1, P_2, P_3$ P_1, P_2, P_3	$(\partial F/\partial V_1), (\partial F/\partial V_2), (\partial F/\partial V_3)$ $(\partial F/\partial V_1), (\partial F/\partial V_2), (\partial F/\partial V_3)$ $(\partial F/\partial V_1), (\partial F/\partial V_2), (\partial F/\partial V_3)$ $(\partial F/\partial P_1), (\partial F/\partial P_2), (\partial F/\partial P_3)$ $(\partial F/\partial P_1), (\partial F/\partial P_2), (\partial F/\partial P_3)$	0 0 0 0 0
4. Other uncertainty components • Data acquisition system	u_{dNi} u_{N5i}	U_{hor} U_{hor}	1 1	0 0

[9] Spinner Anemometry – Uncertainty Analysis, DTU report I-0384, March 2016

[m/s] • Use of default k constants [%] • Spinner geometry (PC2**) [%] • Rotor induction change [%] • Limitations on algorithm [%]	u_{N6i} u_{N7i} u_{N8i}	U_{hor} U_{hor} U_{hor}	1 1 1	0 0 0

* Index i relates to wind speed bin and numbers refer to IEC61400-12-2 uncertainty designations where possible
** PC2 relates to transfer of NTF to another wind turbine

Combination of uncertainties was then performed with sensitivity factors equal to one and correlation coefficients assumed fully correlated or non-correlated. An example of uncertainty calculation of measurements with a spinner anemometer was included based on a field experiment performed in flat terrain. The results showed a relative uncertainty of 1.4% on the horizontal spinner wind speed. Including NTF uncertainty this resulted in an overall relative uncertainty in free wind speed measurements of below 3.5%.

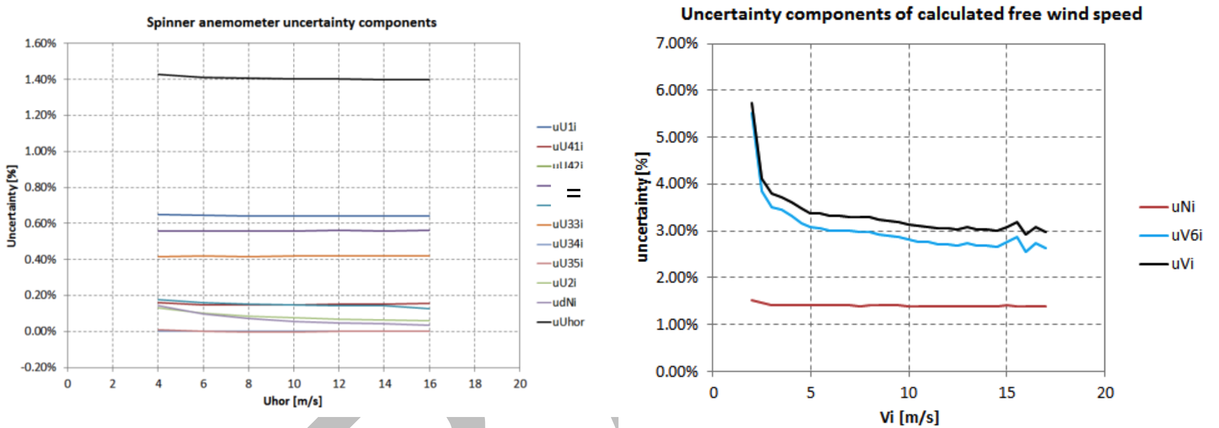

Figure 24: Uncertainty components of iSpin wind speed measurements (left: for horizontal spinner wind speed; right: free wind speed including NTF uncertainty)

Applying the free wind speed uncertainty using iSpin on the AEP (Annual Energy Production) the combined AEP uncertainty covered a range from 7.9% for 6m/s to 4.5% for 10m/s annual average wind speed. For the same annual wind speeds the AEP uncertainty based on met-mast measurement reached from 6.2% to 3.6%, i.e. for the wind speed class of the turbine (TCIIA), the AEP uncertainty using iSpin was 1% higher compared to the met-mast.

Estimated annual energy production at different mean wind speeds. The reference air density is 1.225kg/m^3, cut-out wind speed is 25m/s.						
	Spinner anemometer			Met mast		
Hub height annual average wind speed	AEP measured	Standard uncertainty in AEP		AEP measured	Standard uncertainty in AEP	
(m/s)	(MWh)	(MWh)	(%)	(MWh)	(MWh)	(%)
4	1715	239	13.9	1746	197	11.3
5	3432	348	10.2	3463	277	8
6	5384	428	7.9	5409	337	6.2
7	7185	468	6.5	7203	368	5.1
8	8570	477	5.6	8581	376	4.4
9	9456	466	4.9	9460	369	3.9
10	9886	443	4.5	9883	352	3.6
11	9959	415	4.2	9952	331	3.3

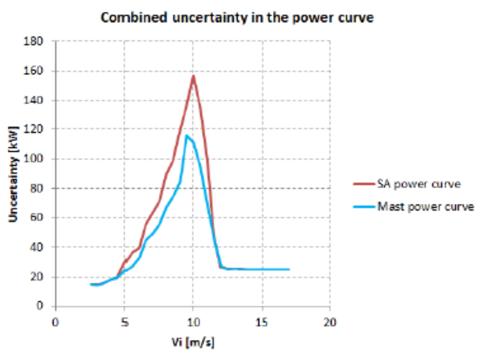

Figure 25. Comparison of met-mast and spinner anemometer based power curve and AEP uncertainties

5.3 Dissemination of the project results

ROMO has obviously published these results on various conferences and in papers over the years. Here is a list of conference presentations, publications and publications in manuscript:

- New method to calibrate a spinner anemometer. Giorgio Demurtas, Troels F. Pedersen. EWEA 2014. March 2014
- Power curves – Use of spinner anemometry, Troels F. Pedersen, Power Curve Working Group, April 2014
- Calibration of a spinner anemometer for yaw misalignment measurements. Troels F. Pedersen, G. Demurtas, F. Zahle. Wind Energy Journal. July 2014
- Advanced wind and power performance monitoring, Karl Fatrdla, VGB Conference, February 2015
- the iSpin technology, Nigel Palor, Karl Fatrdla, Energy Talks conference 2015, October 2015
- the iSpin technology, Nigel Palor, Karl Fatrdla, Wind operator congress 2015, December 2015
- The iSpin technology compared to other wind turbine wind measurement technologies. Henrik S. Pedersen, Harald Hohlen. ROMO Wind report. July. 2015.
- Optimierung von Windenergieanlagen mit der Spinner-Anemometer-Technologie iSpin. Harald Hohlen. 24.-te Windenergietage Spreewind. October 2015
- ROMO Wind's iSpin. Harald Hohlen. WindTech Journal. November 2015
- Use of spinner anemometers. CSH001. IECRE. January 2016.
- Spinner anemometer power curves compared with IEC measurements, Jorgen Højstrup, Henrik S. Pedersen, Eduardo G. Marin, EWEA 2015. November 2015
- Spinner anemometer power curves compared with IEC measurements. Harald Hohlen. AWEA 2016 Wind Project O&M and safety conference, February 2016
- Fallbeispiel: Leistungsoptimierung und –monitoring von Windkraftanlagen mittels Spinneranemometrie; Markus Romber, Karl Fatrdla, Austrian Wind Energy Symposium, March 2016
- All in a Spin, Jan Nikolaisen, PES Wind Journal, April 2016
- A better anemometer gives more accurate wind measurements and monitoring. Karl Fatrdla. Windpower Engineering & Development Journal. April 2016
- Yaw misalignment and Power curve analysis. Henrik S. Pedersen, Eduardo g. Marin, EWEA Analysis of operating wind farms 2016, April 2016
- Holistic performance monitoring of wind farms – the iSpin Guardian approach. Harald Hohlen. Manuscript for VGB PowerTech Journal September 2016

As part of the project Giorgio Demurtas earned his PhD-degree by analysing the power curves of Nørrekær Enge, turbine no 4 and showing that the iSpin transfer function is still 100% stable when being transferred to another turbine (no 5)[10]. The validity of the iSpin transfer function has been shown to depend mainly on installation accuracy of iSpin sensors and this can be made and documented with very high accuracy.

Finally, Vattenfall and ROMO recently agreed to share all raw data from the Nørrekær Enge study with anyone who might be interested in trying to falsify them. ROMO has established a special website (http://romowind.com/en/open-data/), where utilities, students, professors, developers and OEMs at no cost can obtain the data in return for providing their own analysis results to ROMO and Vattenfall. Such transparency has not yet been seen in the wind industry.

[10] *Nacelle power curve measurement with spinner anemometer and uncertainty evaluation, Giorgio Demurtas, Troels Friis Pedersen, Rozenn Wagner, Submitted to Wiley Wind Energy August 2015*

6. Utilization of project results

All data obtained in this project as well as the iSpin X equipment and database, analysis and reporting systems developed are today directly used in ROMO's commercial sales and marketing material and services. All data and the stable cost effective iSpin equipment have been instrumental for ROMO's commercial success, although we still experience a lot of conservatism in the industry regarding decisions to universally rollout iSpin across entire wind farm portfolios. More hard data are the only solution to change this situation. Based on the positive performance studies, ROMO has changed its business plan and sales pitch towards focusing much more on the benefits also of using iSpin for wind farm performance monitoring. The relevant iSpin markets are still: **1)** retrofit on the installed base of existing wind turbines and **2)** new wind turbines.

Ad 1): There are ~260,000 wind turbines installed worldwide. The addressable market for iSpin is the approx. 110,000 turbines equal or larger than 1.5MW installed after year 2000[11] (for older or smaller turbines the business case for installing iSpin for performance monitoring is generally not compelling enough). About 46% of the relevant turbines are in the Americas, 39% in Europe, 12% in Asia and the remaining 3% in Oceania and Africa. We estimate the one-off market for *performance optimization* from *yaw misalignment correction* campaigns to be around €850 million globally[12], and growing with €150m a year as ~20,000 new turbines are installed annually. The market for *performance monitoring* is significantly larger. Pricing for operational and performance monitoring using SCADA data varies between €1,200 to €6,000 per year in Europe[13]. Using the mid-point of €3,600 – which is lower than what ROMO achieves today – the yearly global market for performance monitoring is about €400 million (i.e. €4bn over the next 10 years) and growing with ~€72m a year as ~20,000 new turbines are installed annually.

Ad 2): 2014 saw a record installation of 51,473 MW globally[14]. For new turbines REN21 observed that "*Asia remained the largest market for the seventh consecutive year, accounting for half of added capacity, followed by the European Union (23% in 2014, compared with about 32% in 2013) and North America (13% in 2014, compared with less than 8% in 2013). China alone accounted for about 45% of global additions, followed distantly by Germany, the United States, Brazil, and India*"[15] The current growth rate of about 20,000 new wind turbines a year (assuming an average size of 2.5MW) is expected – especially in light of the COP 21 Paris agreement - to continue for the coming years. The Global Wind Energy Council expects a yearly addition of between 43GW to 60GW per year until 2020 in its New Policies and Moderate Scenarios respectively[16]. China will be the highest growth market.

There is no established market for iSpin for performance measurement and monitoring of new turbines, so estimating pricing is difficult. Traditional nacelle anemometers – unsuitable for performance measurements – have a price in the low single digit thousand euros. The iSpin has a significantly higher value and conservatively assuming an average price of €10,000/unit would bring the market potential to about €200 million per year. Here RW would enjoy a protected position based on the patents, so we should have the possibility to defend pricing over time. It is important to note, that ROMO does not see any other competing technology on the market that can be used for monitoring the per-

[11] *Windpower.net database of globally installed wind turbines*
[12] *110,000 turbines times avg pricing of €7,750 per turbine based on avg size 2.3MW, avg prod hours 2,000, avg prod increase 2.0%, avg global MWh price €42.12 and payback of 2.0 yrs for operator*
[13] *ROMO Wind interviews with providers of SCADA based monitoring services*
[14] *Global Wind Energy Council – Global Statistics 2015.*
[15] *Renewable Energy Policy Network for the 21st Century (REN21), Renewables 2015, Global Status Report, p.70*
[16] *Global Wind Energy Council – Global Energy Outlook 2014, p. 10*

formance of all wind turbines in a wind farm and possibly compare performance between entire wind farm portfolios.

The project recently applied for in the new EUDP application is a key enabler in obtaining general market acceptance for the iSpin technology for universal performance monitoring and consequently further opening up the growing yaw misalignment correction market (retrofit – currently €850m), the performance monitoring market (retrofit – currently €400m yearly), the new turbine market (€200 million per year), plus starting to address the global optimization market of approx. €1.4 -2.6 billion.

The project results confirm the large static yaw misalignment correction market now by having tested more than 300 wind turbines by the use of iSpin. So by correction yaw misalignment the potential of realizing energy policy objectives as described in the original EUDP application has been confirmed. The prospect of further being able to monitor performance, i.e. hence further support turbine optimisation and to be able to intervene in case of underperformance, further support this potential to a much higher extent. This was, however, not foreseen in the original EUDP application.

Dissemination of the PhD results were made in five articles and four reports, presentations at three conferences and in teaching at the DTU course 46400 Wind Turbine Measurements Techniques. Part of the PhD study focused on innovative methods and resulted in a new innovative calibration procedure for yaw misalignment without the use of yaw sensors on the turbine[17].

Apart from the patent application filed before applying for this project ROMO later also filed a patent application on the use of iSpin for pitch control. In addition, 1-2 more patent applications may be filed by ROMO before year-end 2016.

The project has not yet generated increased significantly turnover/export for ROMO, but the increased functionality and stability of the new iSpin X developed during this project are today the basis for all ROMO's commercial sales and marketing material and services, and the new cost effective iSpin X equipment are instrumental for ROMO's future commercial success.

The development of the cost effective iSpin X equipment and new SW applications both for iSpin X and iSpin Yaw has increased the headcount at ROMO with two fulltime electrical engineers, both here in the development phase, but also for the continuous development of further functionalities in the iSpin SW applications.

This project has constituted the key development and demonstration activity in ROMO Wind A/S for the past years. The iSpin technology is the key ROMO platform technology for our entire business. This project and the EUDP support has thus been mandatory for our growth.

ROMO Wind has its R&D department as well as its operation and control centre placed in the international wind power hub, Aarhus, serving the other companies in the ROMO Wind group. Growth of ROMO Wind in general will therefore result in corresponding significant growth of ROMO Wind A/S. This project has directly led to 6 more full-time employees in ROMO Wind as well as to indirect employment because ROMO is outsourcing most of its iSpin installation work to service companies. We expect about 14 additional employees will be hired over the next 1-2 years and further about 20 employees

[17] An innovative method to calibrate a spinner anemometer without use of yaw position sensor, Giorgio Demurtas, Nick G C Janssen, Submitted to Wind Energy Science, July 2015

in 3-5 years. Essentially all ROMO Wind's services are exported. In 2016 our turnover will be about 8.5 million DKK and this number is expect to double over the next 1-2 years. In 3-5 years we expect a turnover and export of about 34 million DKK. However, our continued growth will still be very much dependent on being able to demonstrate the capabilities of the iSpin technology –in particular for performance monitoring – which is why we recently filed another EUDP application.

7. Project conclusion and perspective

This project has been very successful although it has changed direction and focus two times during its extended project period.

This project started out with the main focus on developing and demonstrating a mechanical solution of correction dynamic yaw misalignment. During the study, it was clearly confirmed that the assumed market potential and business case for offering static yaw misalignment correction is indeed still valid. However, it also became clear that correcting dynamic yaw misalignment is much interesting for the market because of limited added commercial benefit. ROMO therefore had to shift gear and develop a highly cost effective, iSpin Yaw electronic solution instead.

In the project period it also became clear that iSpin - in order to be used for permanent turbine monitoring - must be extraordinarily robust and at the same time highly cost effective. Considerable efforts were therefore used successfully on developing iSpin X, which has proven to be a highly reliable product at very reasonable cost. It is furthermore also suited for use on new wind turbines, where iSpin will most likely be connected directly to the wind turbine control system. During the project ROMO also developed a highly effective, automatic data collection, maintaining, analysis and reporting system capable of handling and reporting large amounts of iSpin measurement data to ROMO customers.

Very promising and unexpected results when using iSpin for performance and power curve monitoring for each and every turbine in a wind farm and during the entire wind farm lifetime were obtained during this project (iSpin Guardian principle). The data obtained gave Vattenfall so far unseen and deep insights into the performance of their Nørrekær Enge wind farm enabling them to quantify and intervene if the wind turbines underperform in the future. DTU Wind energy furthermore developed a smart and cost effective iSpin calibration method for yaw misalignment quantification using iSpin. They furthermore put significant efforts into showing that iSpin can measure the wind turbine power curve with high precision and according to the IEC 61400-12-2 standard. Furthermore, DTU Wind energy described in detail the uncertainties related to iSpin power curve measurement, which is of key importance for future uses of iSpin for power curve verification purposes by ROMO and its customers.

The commercial prospect and potential of iSpin being able to verify and monitor all wind turbines being delivered by OEMs is very significant. It is indeed quite stunning that the app. €400 million investment in wind turbines globally was done without knowing if the wind turbines perform according to the manufacturer's warranted specification. Probably less than 5% of wind turbines had their power curve verified at commissioning since met-masts usually not be used in complex terrain, in disturbed wind conditions inside wind farms or offshore. This would be highly unusual in most other industries.

The results from the field test in the Nørrekær Enge wind farm (shown in chapter 5.2.2 The iSpin Guardian approach) strongly indicate that iSpin will be able to change that and provide a universal tool for wind turbine performance verification and monitoring. However, larger field studies confirming this on various turbine types in wind farms located in all types of terrain will be necessary before this option can be commercially realised by ROMO. This is why ROMO applied for yet another EUDP grant in April 2016.

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8. Annex links

/1/ ROMO Wind sales brochure

/2/ Spin v3.0 OEM datasheet. ROMO Wind. May 2016

/3/ New method to calibrate a spinner anemometer. Giorgio Demurtas, Troels F. Pedersen. EWEA 2014. March 2014

/4/ Calibration of a spinner anemometer for yaw angle measurements by use of wind turbine yawing. Giorgio Demurtas. Troels F. Pedersen, DTU Wind Energy I-0305. September 2014

/5/ An innovative method to calibrate a spinner anemometer without use of yaw position sensor, Giorgio Demurtas, Nick G C Janssen, Submitted to Wind Energy Science, July 2015.

/6/ Review of the spinner anemometer from ROMO Wind, iSpin. DNV GL. Report No. 113605-DKAR-R-01. March 2015. Lars Falbe-Hansen

/7/ Calibration Procedure for Spinner Anemometer Yaw Error Measurements. Troels F. Pedersen, Giorgio Demurtas. DTU Wind Energy I-0082. March 2013

/8/ Calibration of a spinner anemometer for yaw misalignment measurements. Troels F. Pedersen, G. Demurtas, F. Zahle. Wind Energy Journal. July 2014

/9/ Increased energy production by optimisation of yaw control. J. Hoystrup; VGB PowerTech. June 2014

/10/ The iSpin technology compared to other wind turbine wind measurement technologies. Henrik S. Pedersen, Harald Hohlen. ROMO Wind report. July. 2015.

/11/ ROMO Wind's iSpin. Harald Hohlen. WindTech Journal. November 2015

/12/ Use of spinner anemometers. CSH001. IECRE. November 2015.

/13/ Spinner anemometer power curves compared with IEC measurements, Jorgen Højstrup, Henrik S. Pedersen, Eduardo G. Marin, EWEA 2015. November 2015

/14/ Power curve measurement with Spinner Anemometer according to IEC 61400-12-2. Giorgio Demurtas. Troels F. Pedersen. DTU report I-0440, version 12/2015 (manuscript)

/15/ Nacelle power curve measurement with spinner anemometer and uncertainty evaluation, Giorgio Demurtas, Troels Friis Pedersen, Rozenn Wagner, Submitted to Wiley Wind Energy August 2015

/16/ Spinner Anemometry – Uncertainty Analysis. Troels F. Pedersen. Paula Gómez Arranz. DTU report I-0384. March 2016

/17/ Relative power curves with spinner anemometry, Troels F. Pedersen. Paula Gómez Arranz DTU report I-0452. April 2016

/18/ All in a Spin, Jan Nikolaisen, PES Wind, April 2016

/19/ A better anemometer gives more accurate wind measurements and monitoring. Karl Fatrdla. Windpower Engineering & Development Journal. April 2016

/20/ Yaw misalignment and Power curve analysis. Henrik S. Pedersen, Eduardo g. Marin, EWEA Analysis of operating wind farms 2016, April 2016

/21/ Holistic performance monitoring of wind farms – the iSpin Guardian approach. Harald Hohlen. Manuscript for VGB PowerTech Journal September 2016