RNRG WHITE PAPER

Wind Iris Operational Applications

Authors:

Brogan Morton

Evan Osler

Guillaume Coubard-Millet

INTRODUCTION

Wind farm profitability is strongly impacted by an operator's ability to assess the performance of individual turbines and use this information to optimize a wind turbine fleet as a whole. Increasingly, the Wind Iris nacelle-mounted Lidar is being used to perform this critical assessment. Because the Wind Iris is mobile, easy to install, and suitable for a variety of applications, it is earning a well deserved reputation as a unique and highly valuable diagnostic tool for turbine performance characterization and optimization.

Many operators understand that the Wind Iris is ideal for detecting yaw misalignment, which can be a very profitable application on its own. However, there are several more uses that take advantage of the Wind Iris's ability to measure the free stream wind up to 400 m in front of the wind turbine. These uses can greatly increase the value of this tool.

This white paper will cover several valuable applications of the Wind Iris using real data from the field, including:

- Yaw misalignment correction
- Operational power curve
- Anemometer nacelle transfer function (NTF)
- Wind sector management

The first three applications—measuring yaw misalignment, operational power curve, and anemometer NTF—are useful for characterizing underperformance, verifying production gains after alignment correction or other turbine upgrades, and identifying safety concerns due to turbine-specific issues. The final application—wind sector management—is more focused on optimizing the wind plant as a whole.

YAW OPTIMIZATION

There are a number of causes of turbine underperformance, some controllable from an operator's perspective and others not. Wind-related causes like poor wind resources or excessive wind flow complexity are impossible to control. Other causes of underperformance can be mitigated and offer the potential for wind turbine asset optimization, including yaw misalignment and blade pitch error. These elements are all controllable to some extent, and they can have a substantive impact on turbine level Annual Energy Production (AEP) as well as the loads seen by the rotor and drivetrain.

The Wind Iris has been used successfully in many yaw misalignment campaigns, in both simple and complex terrain. Of all the yaw misalignment campaigns performed through late 2014, 60% have uncovered yaw errors worth correcting and nearly 30% have found yaw errors in excess of 6°. A yaw error of 6° incurs losses of 1.8% AEP, significantly reducing turbine revenue. For a 2MW turbine with

31% capacity factor and a PPA rate of $60/MWh, this is equivalent to losing $7,767 per year due to a single turbine's inefficiencies.

A large wind farm operator recently deployed a Wind Iris at a Midwest USA wind farm with widespread underperformance. The Wind Iris had been purchased in order to better understand and quantify the underperformance and to look for possible AEP improvement through improved yaw alignment. The Wind Iris was installed by the operator with field assistance from the RNRG Technical Services group in half a day.

The initial measurement campaign had a duration of one month. It became apparent early in the campaign that a static yaw misalignment existed. Figure 1 shows the yaw misalignment estimate and statistical accuracy of the estimate. As time progresses and more upstream wind measurements are collected, the estimate of the yaw misalignment (blue solid line in Figure 1) converges on the actual value. In addition to calculating the average misalignment, the statistical accuracy of the estimate (yellow dotted line in Figure 1) is also calculated and converges in a similar manner. The statistical accuracy represents the range boundary (e.g. +/-0.5°) in which we have a 95% confidence level that the true value falls within our specified range. As more measurements are added, we can reduce the size of the range while maintaining a set confidence level (e.g. 95%)

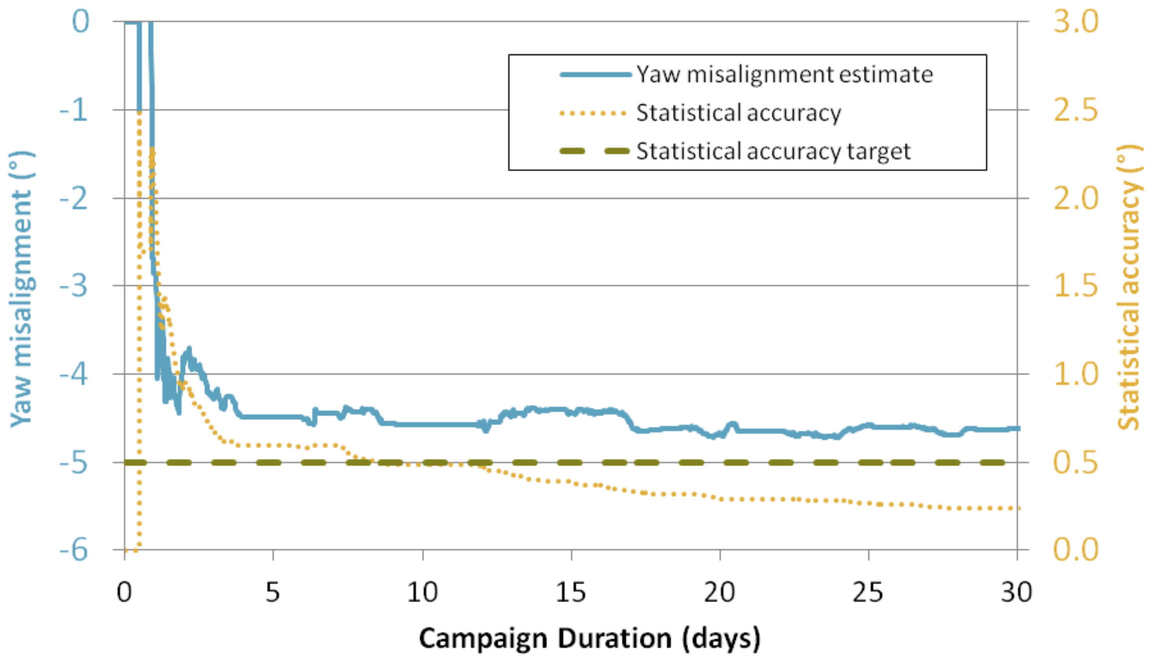

Figure 1. Convergence of the yaw misalignment estimate.

The Wind Iris yaw estimate error crossed the predefined statistical accuracy target (0.5°) within 7 days. That means that the yaw measurement campaign could theoretically have been shortened significantly and repeated on another turbine to increase the return on investment of the Lidar. In this case, however, the operator also wished to measure an accurate baseline power curve, as well as a revised power curve following a yaw alignment correction. The measured yaw error was 5.5°, resulting in an estimated 1.4% AEP loss using the commonly applied cubed relationship between yaw error and AEP.

At the end of the initial measurement campaign, a yaw correction factor of 5.0° was applied to the turbine. In this case, the operator simply changed a yaw offset parameter in the SCADA system. After the correction, another month of data was collected by the Wind Iris. Figure 2 below shows the yaw error distribution from both before the correction (red) and after (green).

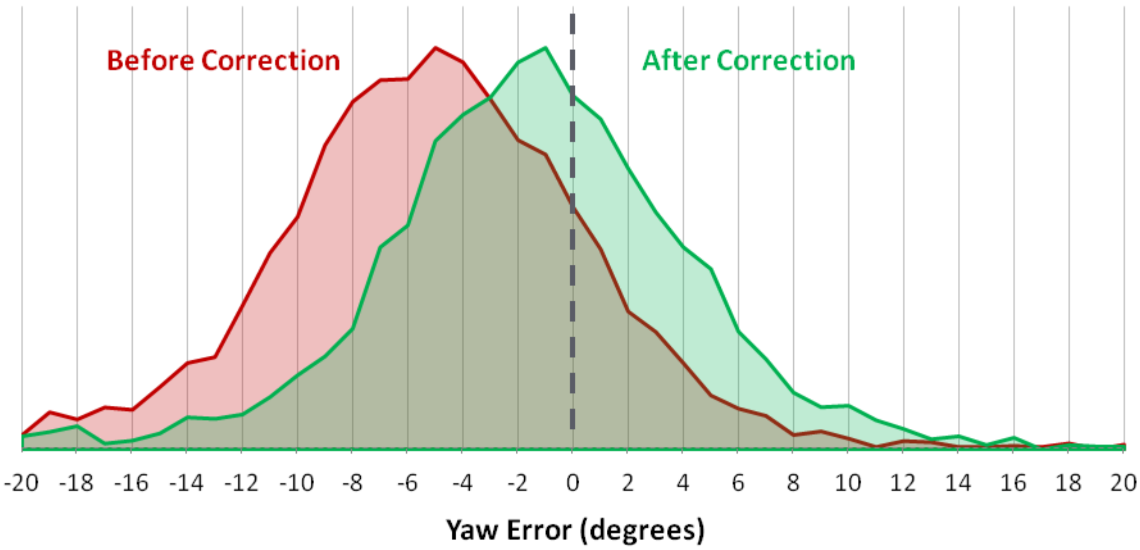

Figure 2. Yaw misalignment distributions before and after correction.

It is important to note that the width of the yaw error distribution is a function of the wind turbine yaw control logic and wind characteristics and therefore remains unchanged after the correction. The mean value of the distribution is shifted due to the static yaw correction that was input into the SCADA system. The width of the distribution would also not be expected to narrow in the event that the Wind Iris or any other nacelle Lidar was permanently installed on the turbine and integrated into the turbine's control system. Since the measured yaw misalignment was 5.5° and the correction was only 5.0°, the mean value of the "corrected" yaw error is 0.5°.

In order to assess the power performance improvement, Figure 3 shows the power curves before and after the correction had been performed following the client's methodology. An improvement of approximately 2% was found:

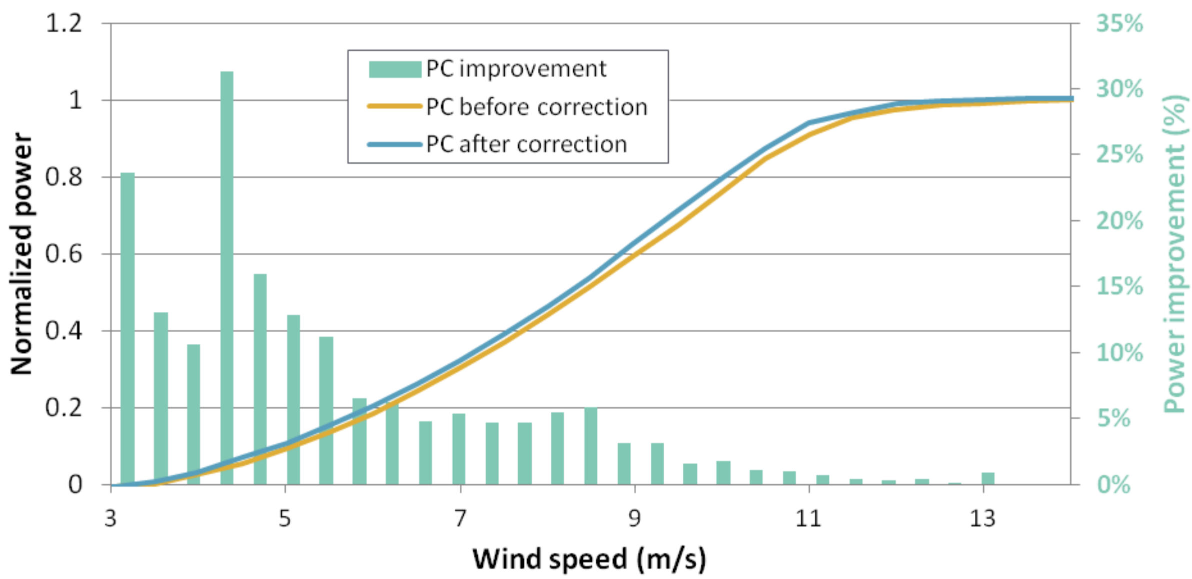

Figure 3. Relative power curve before and after yaw correction.

Similar results have been achieved with First Wind (now SunEdison) and are covered in a separate case study.

Experience from large operators using Wind Iris to date suggests that the magnitude of misalignment does in some cases vary sizably from turbine to turbine within a single farm, whereas in other cases an entire wind farm may suffer from a rather consistent and correctable misalignment. Sufficient sampling of turbines is required in order to draw the latter conclusion.

OPERATIONAL POWER CURVE

In addition to diagnosing problems that can cause turbine underperformance, Wind Iris can also be used to determine whether changes to the wind turbine have increased the aerodynamic performance. Examples of changes can be corrections of yaw misalignment, changes in turbine control sensors, modification of pitch settings, blade cleaning or repair, or the addition of aerodynamic upgrades (e.g. vortex generators, trailing edge serrations). In all these cases, it is important to understand how the change affects the performance of the turbine as well the potential change to the nacelle transfer function (NTF) of the turbine anemometer (sees the ANEMOMETER NTF section below). Since the magnitude of the performance gains are fairly small (1%-2%) with respect to the total variability of the power, it can be difficult to assess the gains with a sufficiently low degree of uncertainty.

One solution to this issue is to measure the power curve of the turbine in an accurate, traceable, and standardized manner to determine if it has shifted. As an illustration, we will use a measurement campaign where the Wind Iris had been used to study the behavior of the turbine performance after the upgrade of the turbine control sensor. The initial measurement campaign had a duration of one

month, which is longer than required to characterize the yaw misalignment but is typical for an accurate power curve analysis when following the requirements for wind speed sample size set forth in IEC 61400-12-1:2005.

RNRG follows the IEC method for calculating the power curve with wind speed measured by the Wind Iris at approximately 2.5 rotor diameters upwind. The Wind Iris has been independently shown to measure wind speed with similar uncertainty to calibrated met tower mounted Class One cup anemometers in simple terrain, and it is therefore considered to be an excellent tool for operational power curve measurements in such terrain. Third-party guidelines provide confidence in this methodology as well as an assessment of uncertainty.[1]

Figure 4 shows the difference between power curves performed using the free wind speed measured by Wind Iris and the nacelle turbine control sensor. Since the new nacelle turbine control sensor was not the stock sensor, the nacelle transfer function (NTF) was inaccurate, resulting in under-measurement of the wind speed. Data was collected by using the wind measurement at 200 m from the Wind Iris and synchronizing it[2] with the power output of the turbine collected by the SCADA system. Filtering of the data follows the IEC61400-1 and DTU procedure (see footnote 1) for power curve measurement using a Wind Iris. The data is then binned per the IEC method to provide a more precise estimate of the turbine performance.

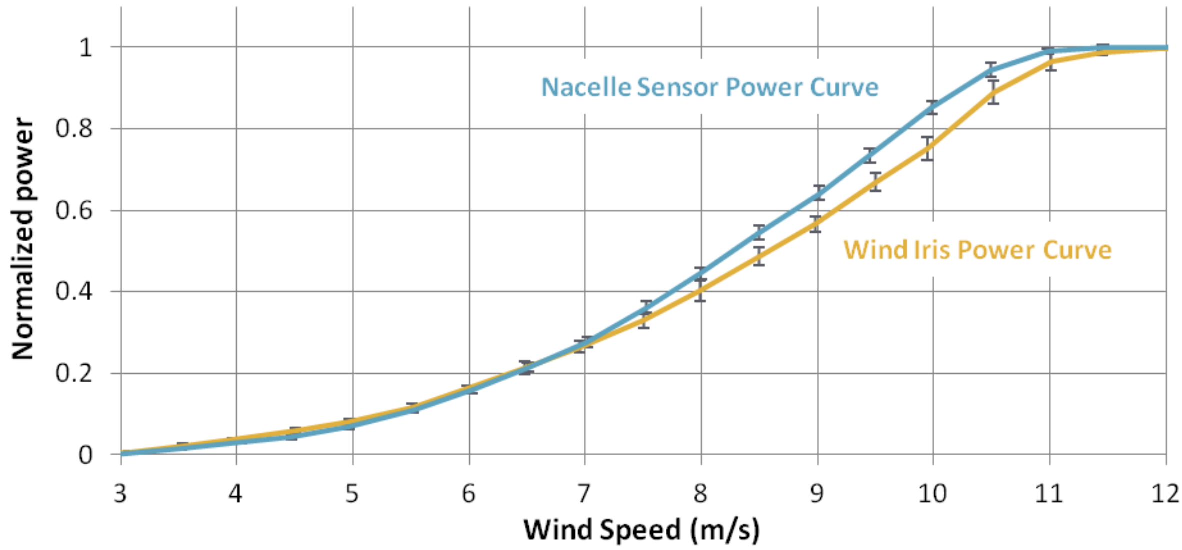

Figure 4. Power curves calculated using Wind Iris measurements at 200 m and the nacelle wind speed sensor.

ANEMOMETER NTF

Given the blocking effect of the turbine on the wind field and the significant energy extracted from the local atmosphere, it is no surprise that the wind speed measured by the nacelle-mounted turbine control sensors deviate from the free flow of the wind ahead of the turbine. Figure 5 shows the effect

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[1] Wagner et al, DTU Wind Energy, “Procedure for wind turbine power performance measurement with a two-beam nacelle lidar”, January 2013. Full report available by contacting info@rnrgsystems.com.
[2] Synchronization was performed in post processing, but could also be achieved through a direct input to the turbine SCADA.

the rotor has on the wind field in front of the turbine using data collected with Wind Iris. To compensate for these confounding effects, wind turbine OEMs create a nacelle transfer function (NTF) that translates the nacelle-based wind measurements into a free flow equivalent set of wind speed and direction.

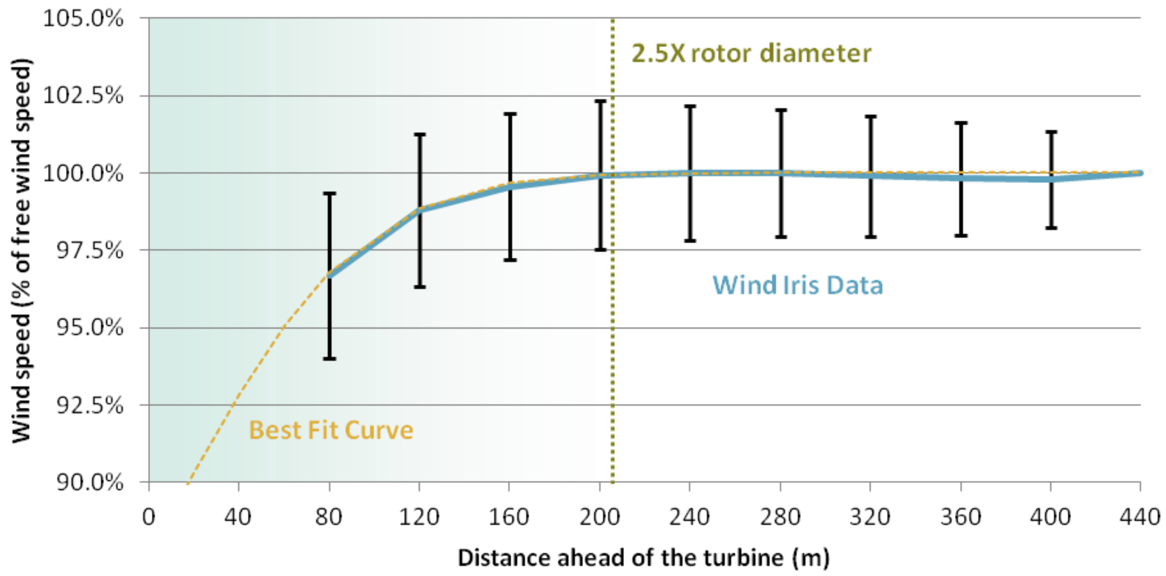


Figure 5. Wind speed measurement ahead of the wind turbine. Significant reduction in wind speed can be seen at closer ranges due to the blocking effect of the turbine.

The accuracy of the wind direction NTF can significantly contribute to the yaw misalignment outlined in the YAW OPTIMIZATION section, especially in complex terrain. If this is not accurately characterized, the compensation that is applied can actually create a yaw misalignment. Since that was covered previously, we will now discuss NTF in term of wind speed.

An accurate wind speed NTF is important for a variety of reasons, including ensuring the turbine operates at maximum aerodynamic efficiency and operates safely in high winds. Some turbines use the measurements of the wind speed to control the turbine tip-speed ratio (λ) so that it can operate at the maximum coefficient of power (C_p). The coefficient of power is the ratio of power captured by the turbine to the total power contained in the wind resource across the rotor diameter. An accurate measurement of wind speed is critical to the performance of these turbines.

In addition to suboptimal performance, there are also safety concerns associated with inaccurate NTF. Wind turbines have a cut-out wind speed threshold, beyond which the blades are pitched out of the wind and the turbine is shut down to prevent damage. On most modern wind turbines, the wind speed measured by the nacelle anemometer is constantly checked against the cut-out threshold. If the NTF is not accurate at high wind speeds, the loading on the turbine can be greatly affected.

The loading on the turbine is greatly affected because the power available in the wind is a cubic function of the wind speed. Consider this example: if a turbine with a 90 m rotor diameter was meant to cut out at 25 m/s, the power of the wind crossing the rotor disk[3] at cut-out is 19.4 MW. If that same turbine has an inaccurate NTF that underestimates the true wind speed by 10%, the power crossing the

[3] $P = 0.5\rho A v^3 = 0.5 * 1.225\ kg/m^3 * \pi * (45m)^2 * (25\ m/s)^3 = 19.4\ MW$

turbine rotor disk[4] at cut-out is 25.8 MW, which is a 33% increase in the rotor disk power. While the turbine will pitch to avoid this excess power, the turbine design margins become much smaller and more load may be placed on the tower, blades, and drivetrain.

Characterizing the wind speed NTF using the Wind Iris is quite straight-forward. "Free stream" wind is typically defined as 2.5 times the turbine rotor diameter. Because the Wind Iris can measure out to 400 m ahead of the turbine, it can easily accommodate all commercially available wind turbines. Using these measurements, it is easy to see the rotor blocking effect as shown in Figure 5. To illustrate the use of the Wind Iris for NTF estimates, let's explore another example from the field.

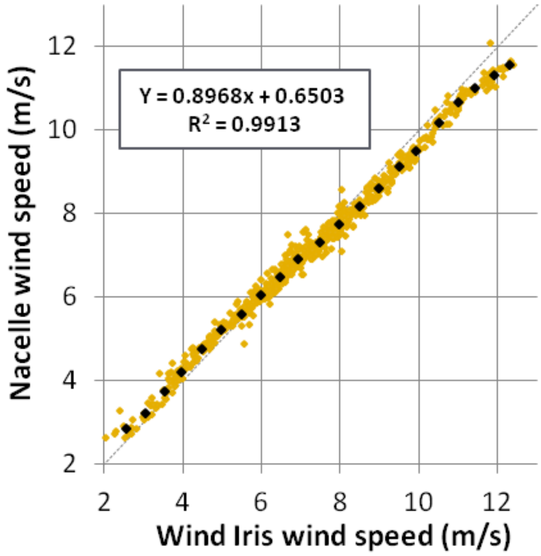


Figure 6. Plot of the nacelle wind speed versus the Wind Iris wind speed.

A different large U.S. wind farm operator recently utilized a Wind Iris to calculate the NTF of a new turbine control sensor that was being rolled out on a plant-wide basis. The sensor was not OEM equipment on the turbine, and the operator wanted to ensure that neither performance nor safety were affected by retrofitting the sensor.

Figure 6 shows the comparison between the free stream wind speed measured by the Wind Iris and the turbine control sensor's compensated wind speed reading. A divergence in the wind measurements, which increases with wind speed, is clear from the data shown in Figure 7. The operator was able to make changes to the NTF and, in this way, was able to confirm safe, reliable operation of the turbines through optimal tip speed ratios, correct high wind cut-out, and proper yaw alignment.

Wind speed NTF values have been shown to vary widely within wind farms and between wind farms utilizing identical wind turbines and control sensors. One independent study performed by comparing

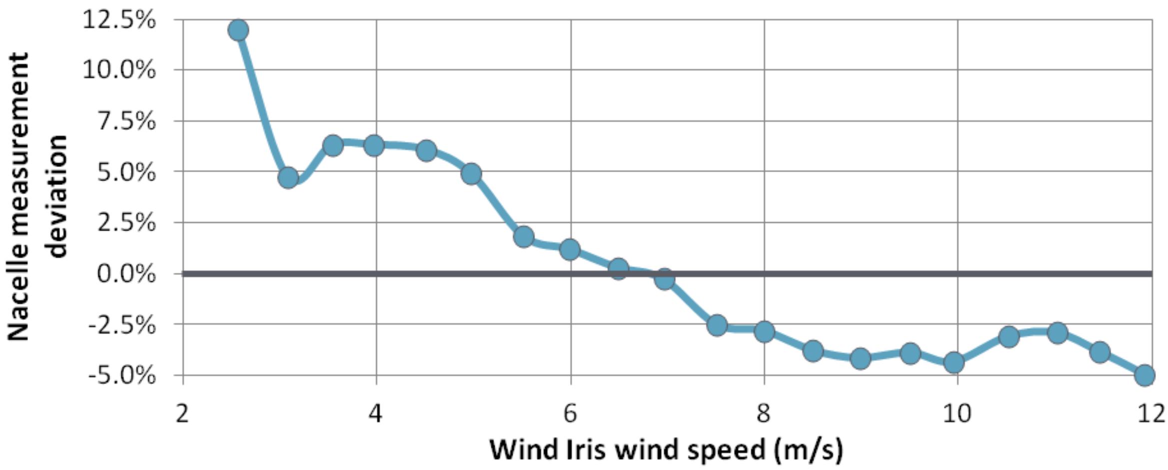


Figure 7. Measurement deviation of the nacelle wind speed compared to the Wind Iris wind speed.

[4] $P = 0.5 * 1.225\ kg/m^3 * \pi * (45m)^2 * (27.5\ m/s)^3 = 25.8\ MW$

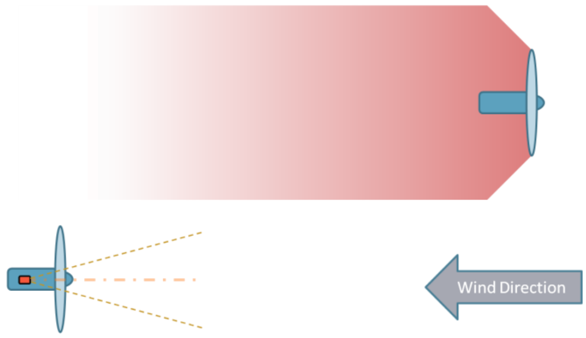
nacelle anemometer values to upstream met towers found a complete lack of correlation between turbine performance measured by the two methods[5].

WIND SECTOR MANAGEMENT

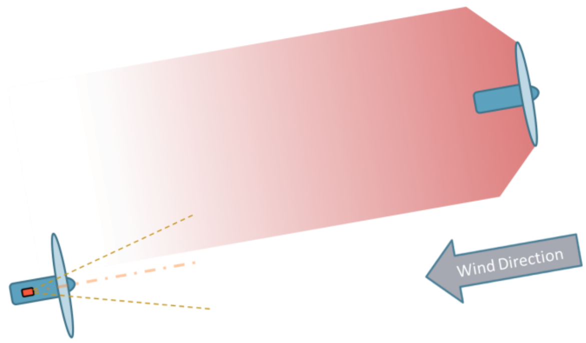
A burgeoning topic in wind plant optimization is wind sector management. When wind plants are designed, there are myriad issues that go into the micro-siting of individual turbines outside of wind resource consideration. The result: when the wind is coming from a particular direction, some turbines on a wind farm will be affected by the wake of others. This can put additional stresses on the downstream wind turbines and affect the power production of the upstream turbine as well. In some cases, it may be beneficial to curtail or downrate one or more of the turbines to reduce loads and increase plant energy production. The turbine OEM typically determines the direction in which the turbine should be curtailed.

Traditionally, these wind sectors are set during the design phase of the project based on data from the wind resource assessment campaign and associated models. This can lead to wind sectors that are suboptimal: possibly too wide due to the inherent uncertainty of the modeling or simply inaccurate enough to cause a downwind turbine to operate in heavily waked flows. Nacelle-mounted Lidars that measure wind at long distances, and at multiple distances simultaneously, allow operators to measure the exact magnitude and width of sectors of wakes and/or high turbulence. This allows operators to refine the curtailment area to be only as wide as absolutely necessary while ensuring the turbine does not operate in waked and highly turbulent flow outside of its design conditions.

The Wind Iris is quite adept at measuring the presence of wakes ahead of the turbine it is mounted on. Figure 8 shows an illustration of the interaction between the wake of the upstream turbine and the individual beams of the Wind Iris. In the first case (top), the wake of the upstream turbine does not interact with the downstream turbine at all, and the Wind Iris measurements are unaffected. In the second case (bottom), both turbines have yawed 15° to the left. At this point, half of the downstream turbine's rotor is affected by the wake. That also means that the left beam of the Wind Iris is in the waked flow. The left beam not only measures lower wind speeds, it also measures much greater wind speed variance (turbulence intensity) caused by the trailing vortices from each of the blades.



When the wind is blowing from the east, the Wind Iris measurement is unaffected by the wake.



As both turbines yaw, one of the Wind Iris beams enters the wake measuring slower wind with much greater turbulence intensity (TI)

Figure 8. Upstream measurement of wakes.

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[5] Creel, Odin. "Cross Site Correlation of Power Performance: Nacelle vs. Meteorological Anemometry". AWEA WINDPOWER Poster, May 2014.

An excellent example of wake sector identification occurred during the NTF campaign mentioned above. There are several different lines of turbines on the site and the turbine being tested is in waked flow for a significant period of time. The figure below shows the layout of the turbines on the wind farm, including the position of a reference met tower.

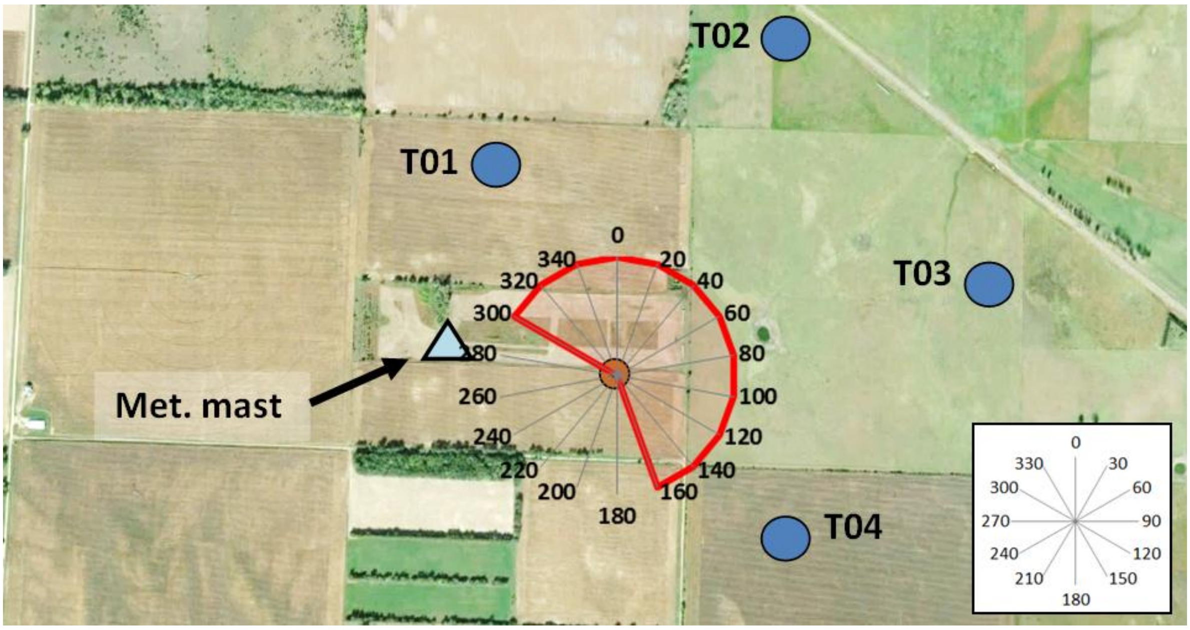

Figure 9. The map shows the location of the test turbine (center), the reference met mast, and several other turbines whose wakes affect the test turbine.

To ensure that the NTF was calculated using only data from wind sectors that were unwaked, the Wind Iris data was used to create filters for the waked sectors. Figure 10 shows the yaw error measurement of the Wind Iris where the wake effects can be seen as large oscillations in the data. The plot was created by synchronizing the Wind Iris measurements with the wind direction data from the reference met tower. It is interesting to note that the amplitude of the oscillation is directly correlated with the distance from the waking turbine. This is consistent with the fact that as the downstream distance

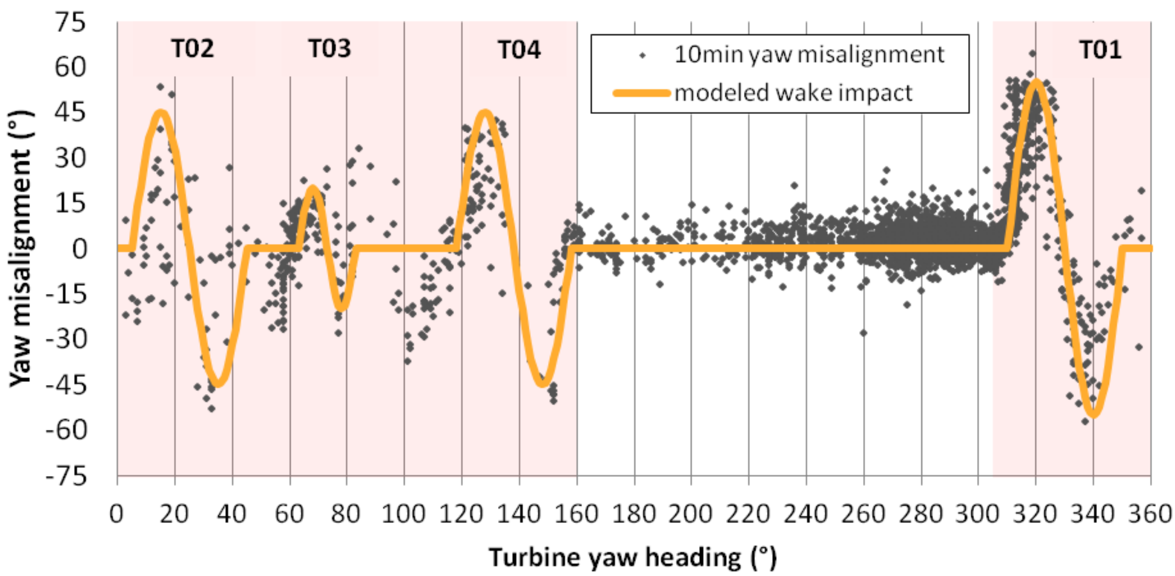

Figure 10. Wakes can be seen as oscillations on a constant yaw error for turbines in simple terrain.

increases, the effect of the wake is reduced, so the difference between the free stream wind speed and waked wind speed is lower.

These oscillations are caused by inhomogeneous wind flow between the two Lidar beams. Figure 11 below shows a graphic depiction of the phenomenon. As the downstream turbine yaws into a wake, one beam of the Wind Iris sees much slower wind speed. This differential in wind speed is interpreted as a directional change due to the vector combination of the two radial wind speed measurements. As the downstream turbine yaws directly into the wake, both beams measure an equivalently reduced wind speed, so the yaw error measurement returns to its baseline yaw error. As the turbine yaws out of the wake in the opposite direction, the oscillation skews the opposite direction.

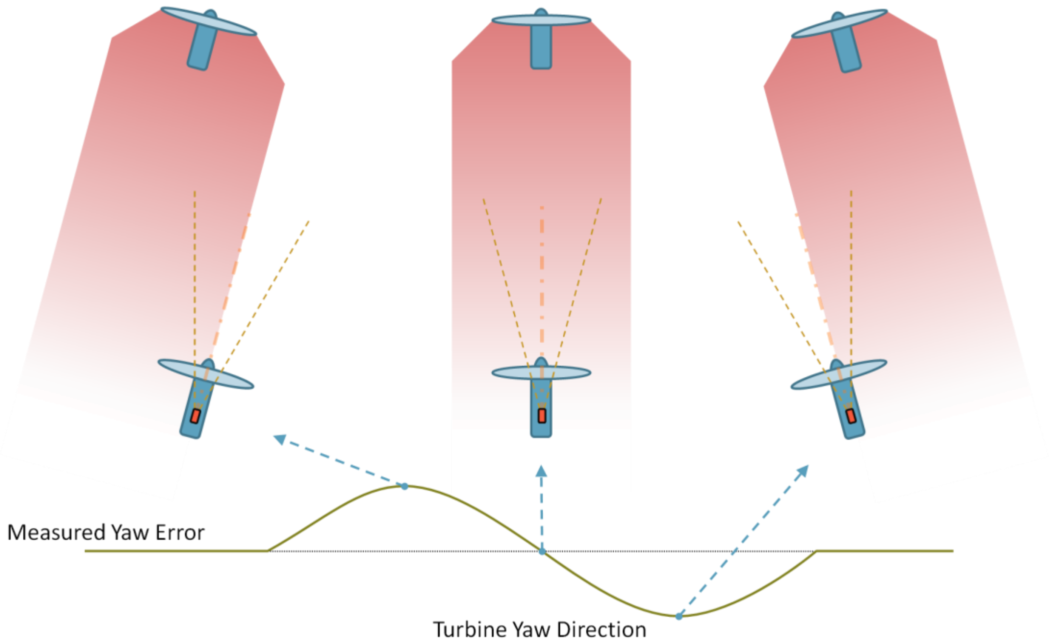

Figure 11. As a turbine yaws through a wake zone, the Wind Iris beams measure inhomogeneous wind flow.

It is important to note that Wind Iris is not the only remote sensor technology that is capable of detecting wind turbine wakes and measuring turbulence intensity (TI). 3D scanning remote sensors (both Lidar and radar) have the capability of illuminating wake behavior in new and novel ways. From an operator's perspective though, they do little to help quantify design load turbulence conditions or provide actionable intelligence for wind direction sector curtailment. The Wind Iris TI measurements exhibit a very high, proven correlation to industry standard cup anemometers, while offering the benefit of always looking upwind from the nacelle it is mounted on.

SUMMARY

As the Wind Iris is increasingly deployed across operating wind farms, its value for large wind farm operators with diverse turbine fleets is becoming very apparent. With this one tool, an operator can increase the AEP of their turbines through yaw optimization, verify the performance increases by measuring operational power curves, and ensure safe and reliable operation by verifying the anemometer NTF. From the wind plant perspective, it can also be used to maximize output and reliability by optimizing wind sector management strategies. The diverse set of uses allows savvy operators to understand and improve plant operations efficiently and in largely unprecedented ways.