Wind Turbine Yaw Misalignment: (R)Evolution

A white paper by

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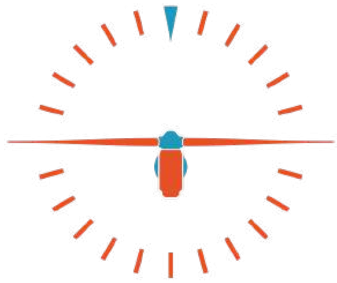

The yaw system is the mechanism all modern turbines have to handle direction changes on the wind. As winds are not constant by nature, wind turbines always need to face the wind to keep generating electricity. In order to do that, turbines are equipped with one or multiple wind sensors that measure the wind direction.

This sensor, either a wind vane or an ultrasonic anemometer, sends out a signal to the turbine controller to yaw the turbine some degrees right or left when a wind direction change is detected.

YAW MISALIGNMENT IS DEFINED AS A WIND TURBINE NOT APPROPRIATELY ALIGNED TO THE WIND FLOW

What does happen, however, if this sensor is not providing the right signal to the turbine? Or if the turbine controller is not interpreting the signal well? We define a yaw misalignment as the condition where a wind turbine is not appropriately aligned to the wind flow. This phenomenon can be seen in two different situations.

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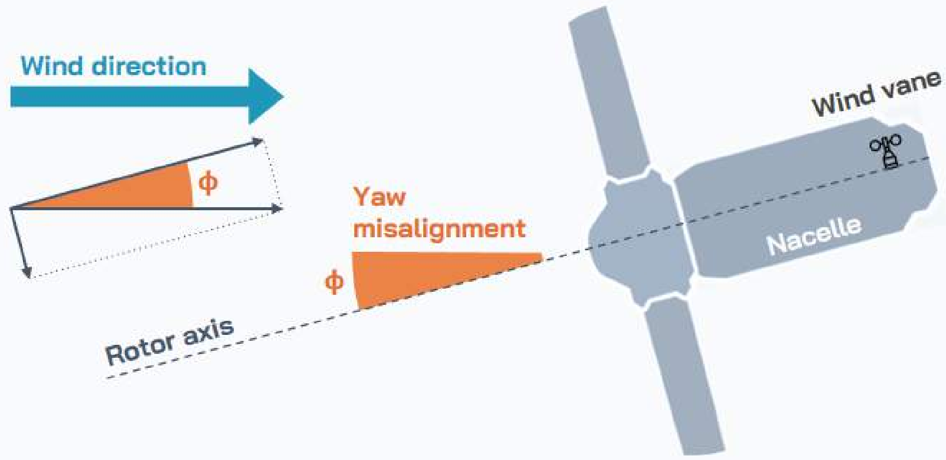

FIGURE 1. DEFINITION OF YAW MISALIGNMENT

First, when the signal is always offset from the real wind direction, we are speaking about a static yaw misalignment (which can be seen when the turbine and wind direction are not changing but the turbine remains misaligned compared to the wind direction).

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However, sometimes it occurs that the turbine is just too slow to orientate itself to the wind direction - i.e. the signal from the wind vane takes too long to arrive at the controller, or the controller waits too long before giving the order to rotate the turbine. When this occurs, we are speaking about a dynamic yaw misalignment, which is linked to the reactivity of the yaw system.

A yaw system with low reactivity will have a significant degree of dynamic yaw misalignment, even if its static yaw misalignment is zero.

OVER 50% OF TURBINES OPERATE WITH MORE THAN 6° OF STATIC YAW MISALIGNMENT

And why are these two issues so important for wind turbines and for the wind industry? Both a static or dynamic yaw misalignment will reduce the power output of a wind turbine. As the turbine is not facing the wind, or is too slow to adapt to its changes, it will capture less energy than what is available to it.

Additionally, the major components of the turbine (blades, drive train, etc.) will suffer higher loads if the misalignment is beyond its design envelope, potentially leading to a lower lifetime for the wind turbine. Recent studies suggest that over 50% of turbines operate with more than 6° of static yaw misalignment(1).

In this whitepaper the current status of this significant performance issue will be studied in detail, understanding its effects on turbine performance and lifetime. A thorough review of the current technologies to detect, correct and monitor static yaw misalignment will be presented, together with the introduction of a novel approach that allows for more cost effective monitoring than current techniques.

Visualizing & understanding the Issues

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In order to understand how a yaw misalignment is detected, first it is important to define the method used by modern wind turbines to yaw into the wind. For that, the following parameters are considered:

- Absolute Wind Direction: the direction from which the wind comes from, measured in ° from 0° to 360°.
- Turbine Position: the direction that the turbine is facing with reference to the True North. This is again measured in ° from 0° to 360°.
- Relative Wind Direction: this is the wind direction as seen from the nacelle, therefore using the coordinate system of the turbine position. This is measured in ° ranging from -180° to +180°, and can be defined as well as the yaw error.

The three parameters above are linked to each other with the following equation:

ABSOLUTE WIND DIRECTION =
TURBINE POSITION + RELATIVE WIND DIRECTION

When there is a change in absolute wind direction, a relative wind direction above 0° is measured and the turbine controller sends a signal to start yawing, allowing the turbine to re-align its turbine position to the new wind direction. Presented like this, it could seem that turbines cannot become yaw misaligned.

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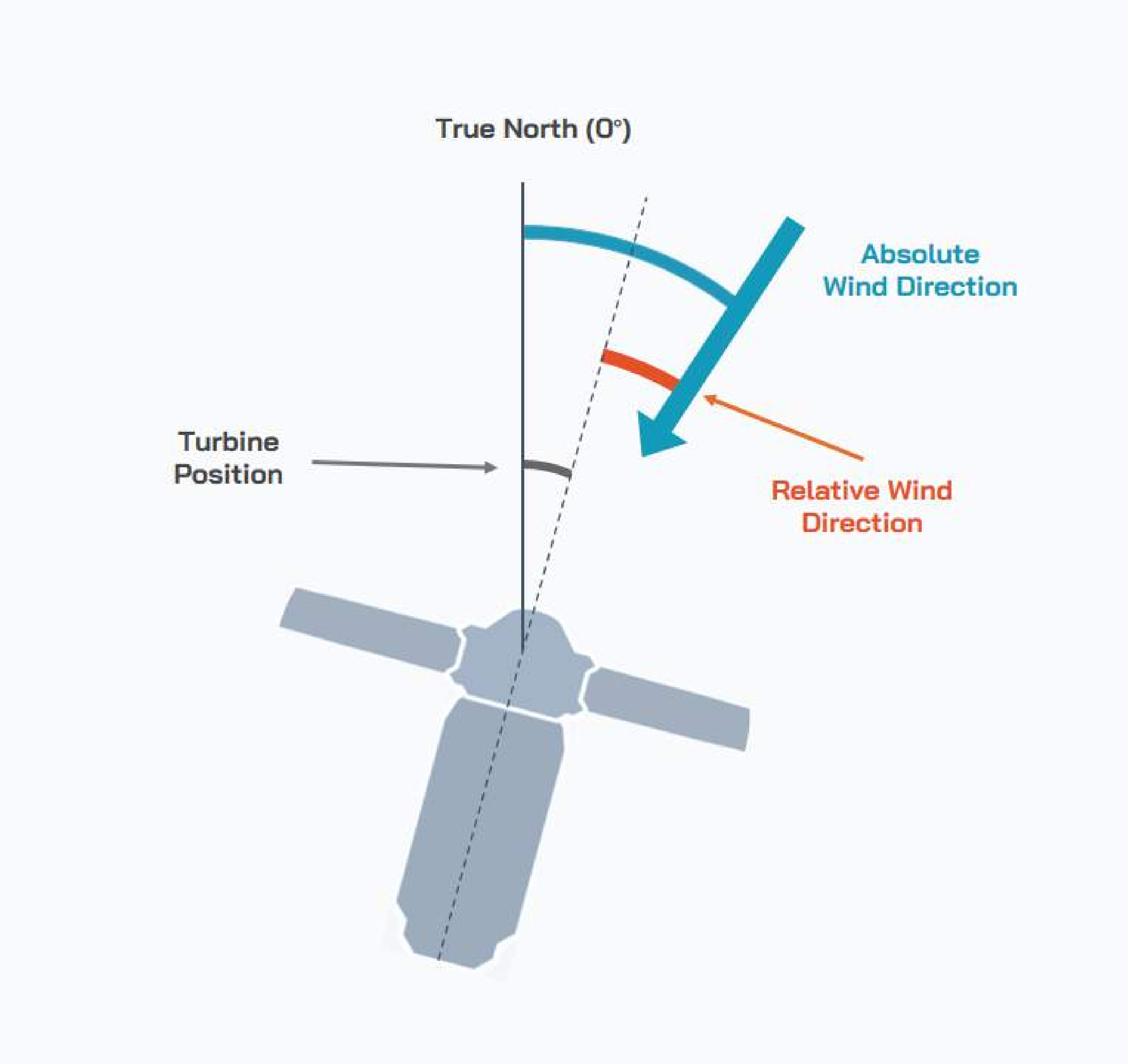

FIGURE 2. DEFINITION OF TURBINE POSITION AND WIND DIRECTIONS

However, there are several circumstances when this mechanism will not be accurate. If the turbine wind sensor was not measuring the wind direction correctly, for example, the turbine would think it is well aligned, when in reality, it is not. It is for that reason that using an independent wind direction measurement device can highlight differences between the turbine measurement and the real measurement.

The best way to understand the logic explained earlier and how that is affected by a yaw misalignment is visualising the distribution of relative wind direction (or yaw error).

This basic graph easily demonstrates whether a turbine is suffering from a static yaw misalignment as the centre of the distribution should be close to 0° for well aligned wind turbines. If the center of the distribution is shifted towards positive or negative angles, this means that the turbine is suffering from a yaw misalignment, its value being the center of the distribution (see Figure 3).

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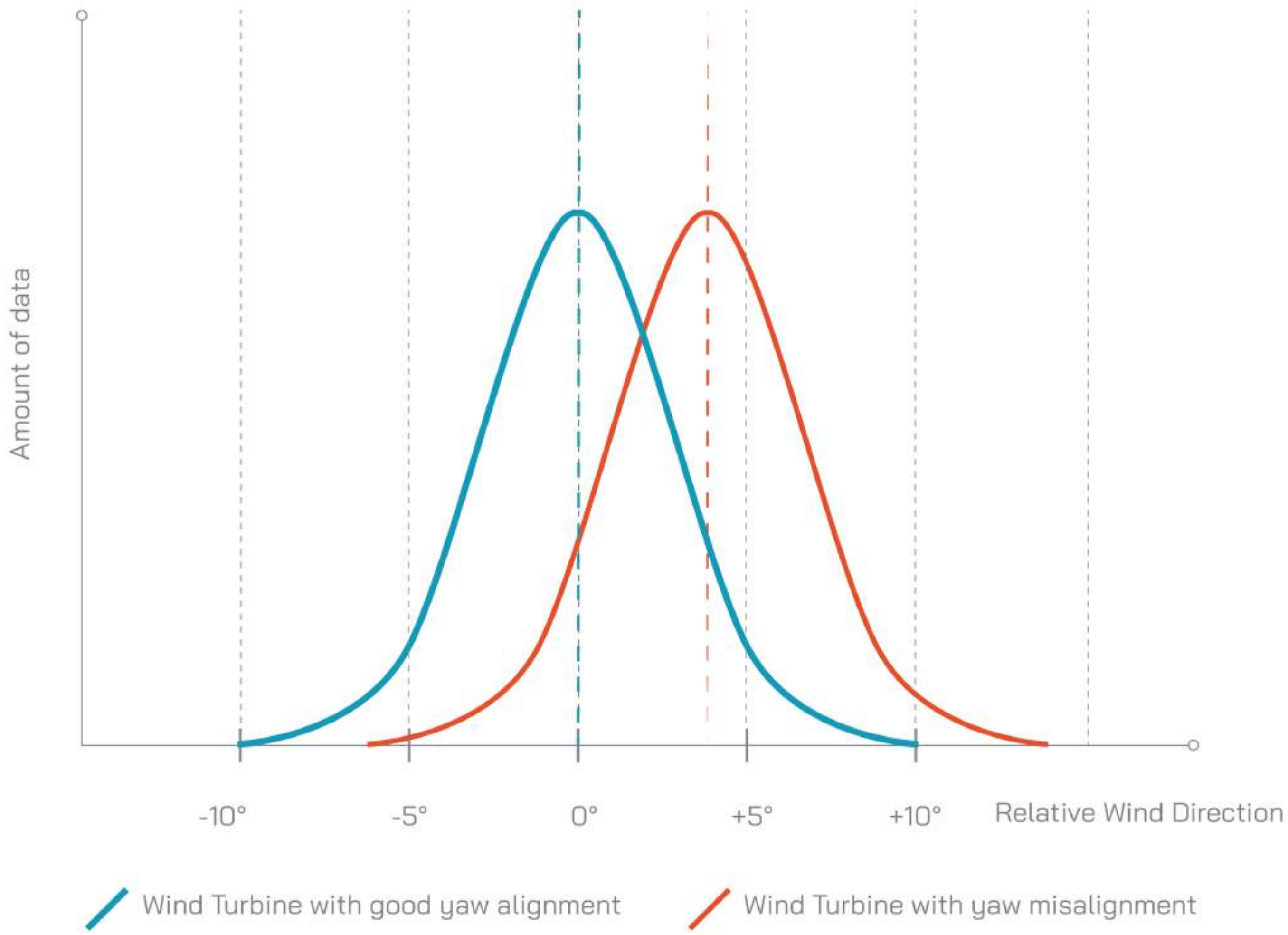
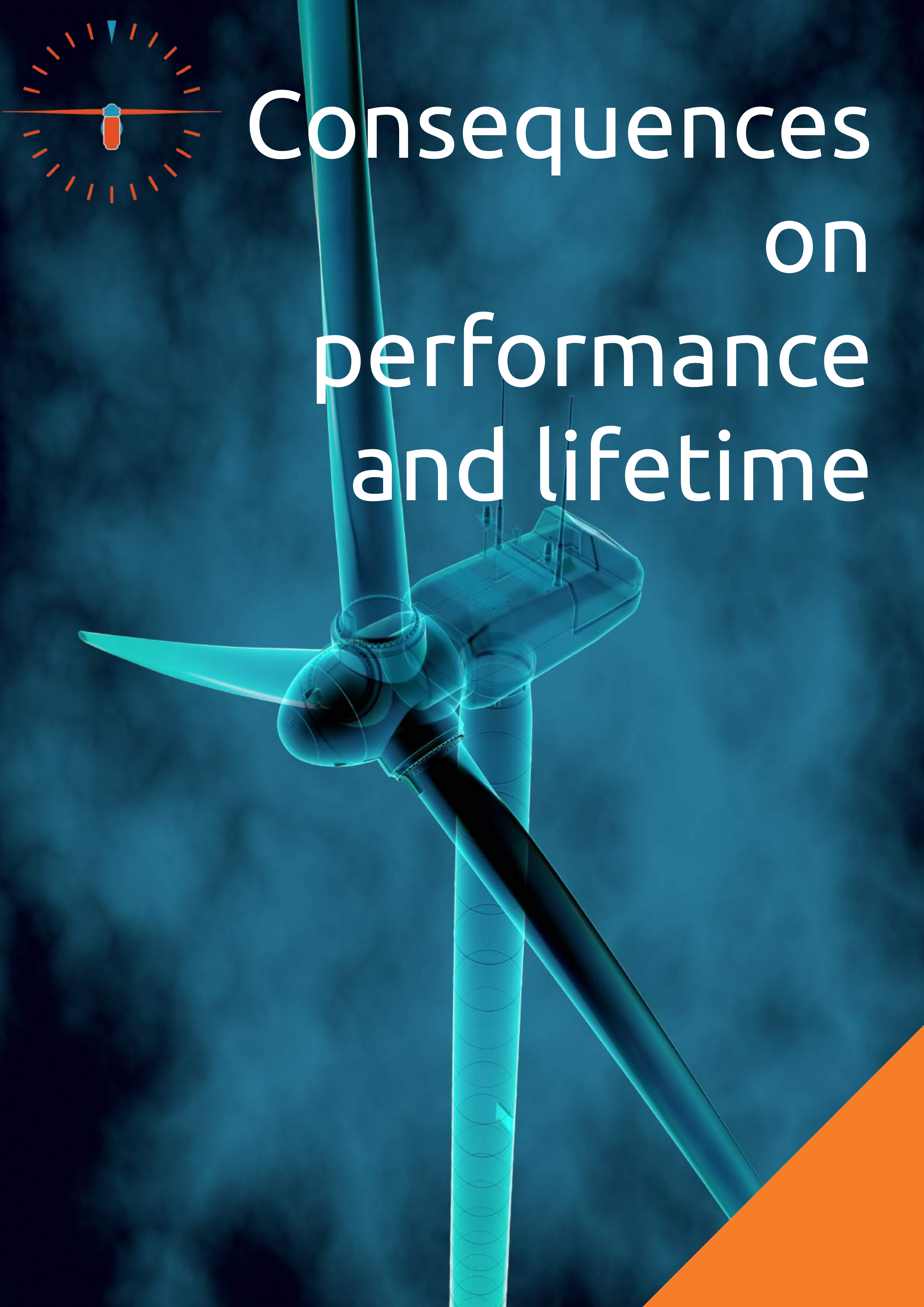


FIGURE 3. TURBINES WITH DIFFERENT YAW MISALIGNMENTS.

Consequences on performance and lifetime



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The impact of yaw misalignment on the power output capability of wind turbines can be understood from the following perspective: as the rotor is not completely perpendicular to the wind flow, the effective wind speed captured by it will be the cosine function of the yaw angle (see Figure 1).

As power output has a cubic relationship with wind speed, it can be assumed that the power loss is directly proportional to the cubic cosine of the yaw misalignment(2). This assumption has been further supported by theoretical studies using Blade Element Momentum theory (BEM) that define the cosine exponent (α in the equation below) equal to 3(3).

$$\text{POWER LOSS (\%)} = 1 - \text{COS}^{\alpha}(\text{YAW MISALIGNMENT})$$

This value, however, has been found to overestimate the power loss in several studies using field measurements from wind turbines(3)(4). Several of these studies found the value of α to be around 1.8(5).

Considering this value can vary from 1.7 to 5.1(6) depending on external factors such as the atmospheric conditions, the turbulence nature of the wind, or whether the turbine is affected by wake situations(7). To summarise, the widespread agreement across the industry is to consider **α** = 2 (see figure 4) for all cases, even though it is proven that this remains widely uncertain.

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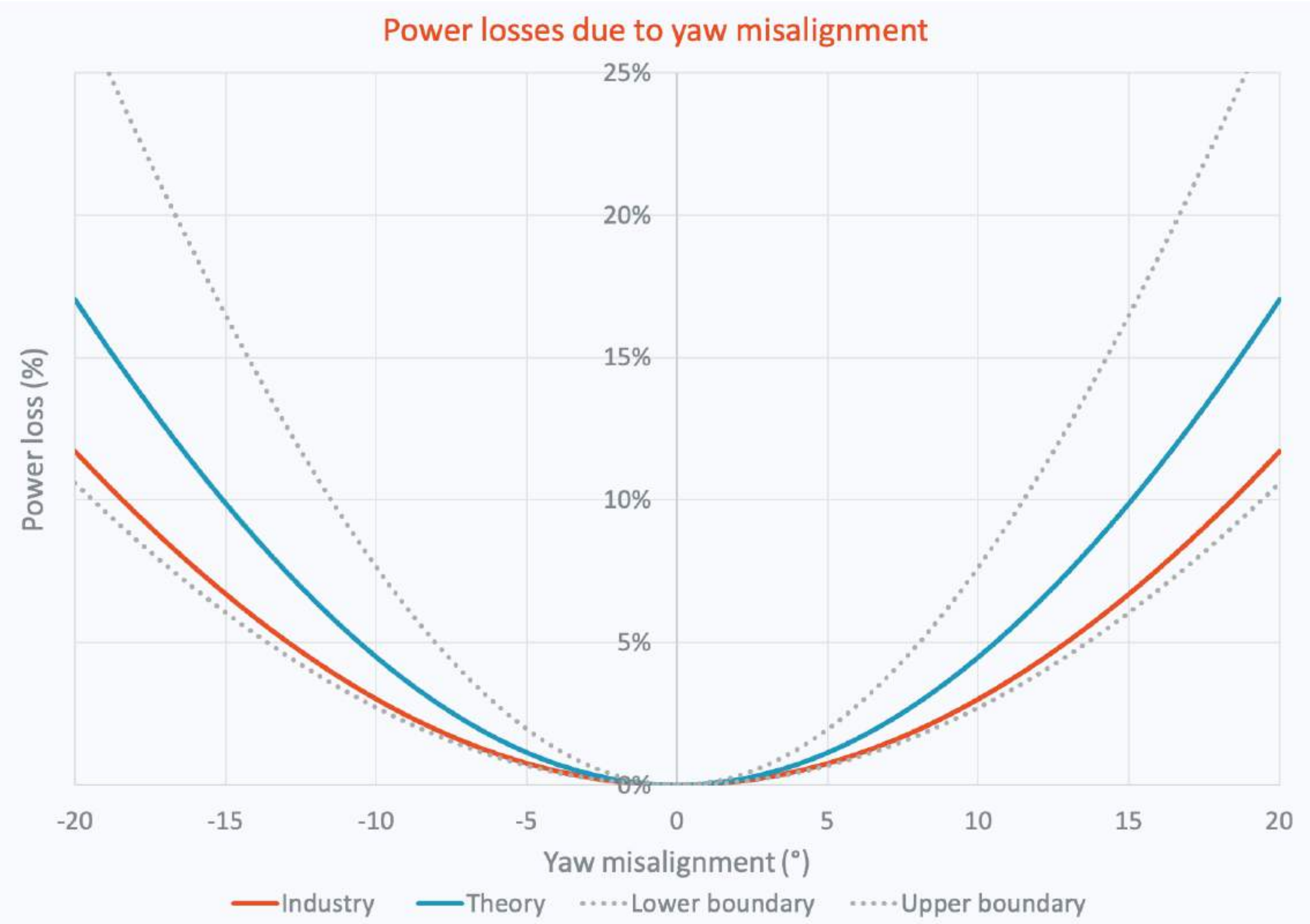

FIGURE 4. POWER LOSS AS A FUNCTION OF YAW MISALIGNMENT FOR DIFFERENT CASES.

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Figure 4 presents the different values discussed above. The X axis represents the yaw misalignment in ° whereas the Y axis shows the % of power loss. Different **α** values are shown, including the Industry standard (**α** = 2), the BEM theory (**α** = 3) and the possible ranges based on field studies. In most cases, small misalignments (up to 3 to 4 °) will have negligible power losses (well below 1%), whilst this loss will become more critical for larger yaw misalignments being able to reach up to 3% for a 10° misalignment .

Another aspect that remains largely unknown is how the wind distribution on a particular location will affect the performance loss caused by yaw misalignment. A turbine suffering from a misalignment will have a degraded power curve, but it will be able to operate at rated power for high wind speeds. This implies that yaw misalignment losses will become a lot more important for low wind speed sites, as the power loss only affects the turbine operation below nominal power.

IMPACT ON LIFETIME

The impact of yaw misalignment is widely considered within the design standards of modern wind turbines. The latest IEC edition(8) contemplates yaw misalignment conditions of different degrees depending on each Design Load Case (or DLC, the operational conditions linked with external factors that turbines are certified against).

In general, all wind turbines certified according to this IEC are supposed to withstand static yaw misalignments of up to 8° on normal operation conditions and up to 30° during extreme weather conditions when turbines are not operating.

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Even though the values from the IEC norm can seem quite large, the effects of yaw misalignment on turbine loading and lifetime have been studied through both modelled and field experiments and found to be relevant for lower yaw misalignment values.

NO GUARANTEE THAT TURBINES ARE OPTIMISED FOR MAXIMUM PERFORMANCE OR LONGEST LIFETIME.

Some studies(9) showed that all turbine major components (blades, drivetrain and tower) will suffer higher Damage Equivalent Loads factors under yaw misalignment conditions after measuring the effects on test turbines. Both the fatigue and extreme loading were found to increase in most components, suggesting that turbines with yaw misalignment do not only have a shorter lifetime but can as well be prone to significant structural damages under extreme conditions such as storms.

In addition Fleming et al(10) showed that the loading on the blades can increase by up to 10% when a 10° yaw misalignment is present (depending on the yaw misalignment direction), and that both the yaw bearing and tower loading can increase by similar values for both positive and negative yaw misalignments.

State of the art: current technologies

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Several technologies have been consolidated these last few years to detect yaw misalignments since this issue became relevant to wind owners as one of the key drivers to optimal performance in the early 2010s.

The following section presents a benchmark of the most frequently used technologies across the industry, comparing them on their accuracy and cost. Special emphasis is given to the capability each technology has to provide continuous monitoring of yaw alignment condition, as it has been observed that degradation of turbine sensors over time occurs(11)(12).

The resulting evaluation is presented on the table below, followed by more details on the assumptions considered for each technology.

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Technology		Accuracy	Cost	Suitable for continuous monitoring
	Meteorological mast or ground based LiDAR			No
	Nacelle mounted LiDAR			No
	Spinner anemometer			Yes
	SCADA data			Yes
	OEM products			Yes
	Windfit			Yes

TABLE 1: TECHNOLOGIES BENCHMARK

Meteorological masts or **ground based LiDARs** can provide the highest accuracy when it comes to measuring wind flow before it reaches the wind turbine. These devices measure wind speed, direction, shear, veer and turbulence intensity, which allows them to obtain a very detailed characterisation of the wind flow. Thanks to their high accuracy, these technologies have been widely used by researchers to understand the effects of yaw misalignment(12).

Some minor disadvantages are related to the data synchronization or North deviation differences between the external measurement devices and the turbine SCADA(11), but by far the main drawback of such method is the prohibitive cost of permanent met masts (and, to an extent, ground based Lidar units). A determining reason why this method is only within reach of research institutions and is not being considered for industrial deployment nor capable of providing a continuous monitoring for wind turbines.

An innovative iteration on the use of LiDARs consists of placing them on top of the nacelle pointing horizontally towards the wind flow (**Nacelle-mounted LiDARs**), obtaining therefore the wind flow information several meters before it impacts the rotor. This is considered one of the most precise methods to detect yaw misalignments and has become the prefered method by most researchers and performance experts(13)(14).

Some limitations of this technology include possible issues with the wind field reconstruction under wake conditions(15), the requirement of making permanent modifications to the nacelle when installing the devices or their high cost (specially when considering long range LiDARs), which deem them not capable yet for permanent monitoring of yaw misalignment.

Short range LiDARs (which measure the wind flow around 10m in front of the rotor, instead of the 50 to 200m distances for long-range LiDARs) come at lower cost but with further limitations (the same that affect **spinner anemometers**) as they measure directly into the wind turbine rotor induction zone, where the wind flow is heavily disturbed by the external conditions and the turbine design itself (spinner shape, blade root design, etc.).

This means that calibration functions need to be implemented (similar to those used for the wind turbine wind sensors) hence increasing the uncertainty of the final results(16).

Finally, significant effort has been made in order to achieve a precise detection and monitoring of yaw misalignment using **SCADA data**(11)(17).
The benefits are obvious: low cost, as there is no need for installing additional equipment, plus the capability to continuously monitor the alignment condition.

These methods use a combination of turbine parameters like the relative wind direction as measured by multiple turbine anemometers or the rotor RPM to identify abnormal behaviours between turbines. The studies above showed that 10 minute SCADA data from the turbine can, to a certain degree of accuracy, detect anomalies on the turbine alignment, even though a more sophisticated method is required in order to quantify the degrees of misalignment.

One of these more refined methods consists of using Maximum Power Point Tracking (MPPT) algorithms within the wind turbine controller to continuously align the wind turbine to the wind flow.

These methods, usually offered by wind turbine manufacturers (**OEM products**), rely on a closed loop control of the turbine operating conditions where yaw misalignments are imposed for short time periods to identify the optimum turbine alignment. Even though these are more accurate than simpler SCADA methods, their reliance on turbine sensing technology acquiring data at low frequency make them highly dependent on the wind conditions and slow to react to changes in the wind regime, thus reducing their overall accuracy.

All the technologies discussed above present their own benefits and can be suitable for some of the industry needs. It can be concluded, however, that none of them are considered so far the leading method used for fleet wide monitoring of yaw misalignment. The following section presents an innovative approach where high frequency measurements are used for yaw misalignment detection and monitoring, showing a better cost / benefit ratio than currently used technologies.

Introducing a new approach to yaw misalignment monitoring

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INDEPENDENT DATA FROM GENERATION TO PROCESSING AND DISPLAY

In this section an innovative technique using a combination of wind speed, wind direction and power measurements is presented, highlighting its advantages over the traditional methods discussed in the section before.

Previously, some significant shortcomings of the current methods have been described, like the need to install costly equipment, the poor precision of standard SCADA data or the impossibility to deploy accurate solutions at scale. Having these weaknesses in mind, a novel approach has been designed that allow not only to detect existing yaw misalignments, but to perform a continuous monitoring that can be deployed at a large scale.

This technique consists of using an independent device that continuously measures wind speed, wind direction and turbine power output at higher resolution than standard SCADA data (up to 4 Hz). All the acquired data is transmitted to the cloud using the 2G or 4G phone network on the site, independently from the SCADA network. On the cloud, several algorithms evaluate all the stored and new data to provide a continuous diagnosis of the yaw misalignment condition of each wind turbine. The details on how this diagnosis is obtained are explained on Figure 6.

COMBINING WIND SPEED, DIRECTION & POWER

The reason for using high frequency data comes from the changing nature of the wind. The rate of change for wind speed and wind direction is of the order of seconds, whilst the turbine dynamic response is usually around the minute scale (i.e. the wind direction can change after a few seconds, whilst the turbine will take a few minutes to respond to this change). In any case, both changes will be poorly captured by 10 minute SCADA, highlighting the need for measurements at higher resolution(11).

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In fact, this higher resolution helps to understand the turbine response to fast yet significant variations on wind direction, which allows to characterize the turbine performance under different yaw conditions and thus identify the optimal alignment to maximise its output.

This point brings up the second main principle of this novel technique: optimising for maximum power, not for best yaw alignment. It has been found that turbines might perform better when small degree misalignments are present, instead of being completely perpendicular to the wind direction, suggesting that optimal power point tracking is preferable than optimal alignment(18).

OPTIMISING FOR BEST ALIGNMENT = MAXIMUM POWER

The reasons for this are not yet very well known: some argue that the rotor asymmetry (as the rotor always spins on the same direction) coupled with the blockage effect of the same rotor could be behind this effect, whilst other have pointed out that measuring the wind flow as a single point in space (either in the front of the turbine using a nacelle LiDAR or behind using the turbine anemometers) cannot be representative of the overall wind flow, specially for large rotors and in complex terrain, where the wind flow can be rather chaotic.

To summarise, the key principles of this solution are:

- High frequency wind measurements to capture with a high level of detail the behaviour of the wind.
- Combining such measurements with high frequency power measurements to characterize the response of the turbine to such fast changes in wind behaviour.
- Continuously seek the optimal alignment of the wind turbine to **maximise** its **performance**.

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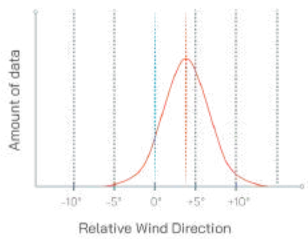
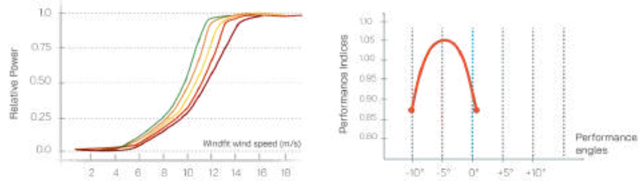


DEFINE CURRENT TURBINE ALIGNMENT

Wind speed and wind direction measurements are evaluated to identify the most frequent relative wind direction.

Example of a distribution of relative wind direction values: The most frequent relative wind direction is observed around 4°.

A power curve for each 2° wind direction bin is defined in order to calculate a performance index. The best performing wind direction is observed around -5°



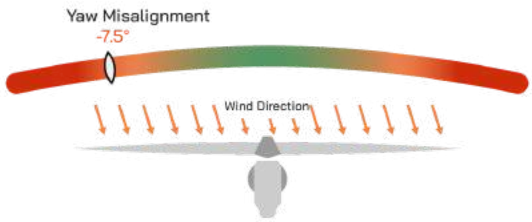
IDENTIFY OPTIMAL ALIGNMENT

High frequency power curves for each relative wind direction are generated and compared to identify the best performing alignment.

IMPLEMENT NEW ALIGNMENT

The difference between the most frequent and the best performing alignment is the correction to be implemented on the turbine.

In this case, the wind turbine needs to be realigned 7.5° to the left to maximise its performance.



VALIDATE NEW ALIGNMENT AND CONSTANTLY MONITOR

As soon as the correction is implemented, measurements will allow to confirm the new alignment and the increase in performance.

A 12° yaw misalignment is corrected to reduce its value to <1°

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Having tested this technique on more than 500 turbines on the field, and having compared the results against other technologies like nacelle LiDARs in multiple cases, the following **advantages** for this novel technique have been identified:

- It is well suited for the permanent monitoring of all turbines within a wind farm, in comparison to LiDAR techniques where the measurement unit needs to be moved around the wind farm carrying out time-limited measurement campaigns on each turbine.

- It has a much higher level of accuracy than SCADA methods, and is not far from the precision of more expensive technologies like nacelle LiDARs.

- It provides results much **faster than all the traditional methods**, being able to detect a change in the yaw misalignment condition in a matter of days.

- It avoids some of the constraints highlighted on other methods, like a difficult and intrusive installation, or the issues caused by data synchronization or north deviation when using separate data sources.

Finally, when considering all the advantages of this novel technique and comparing it to all traditional methods used so far on detecting yaw misalignments, it can be concluded that this new technique results on being the most cost effective solution to identify and monitor wind turbine yaw misalignment at a wind farm scale.

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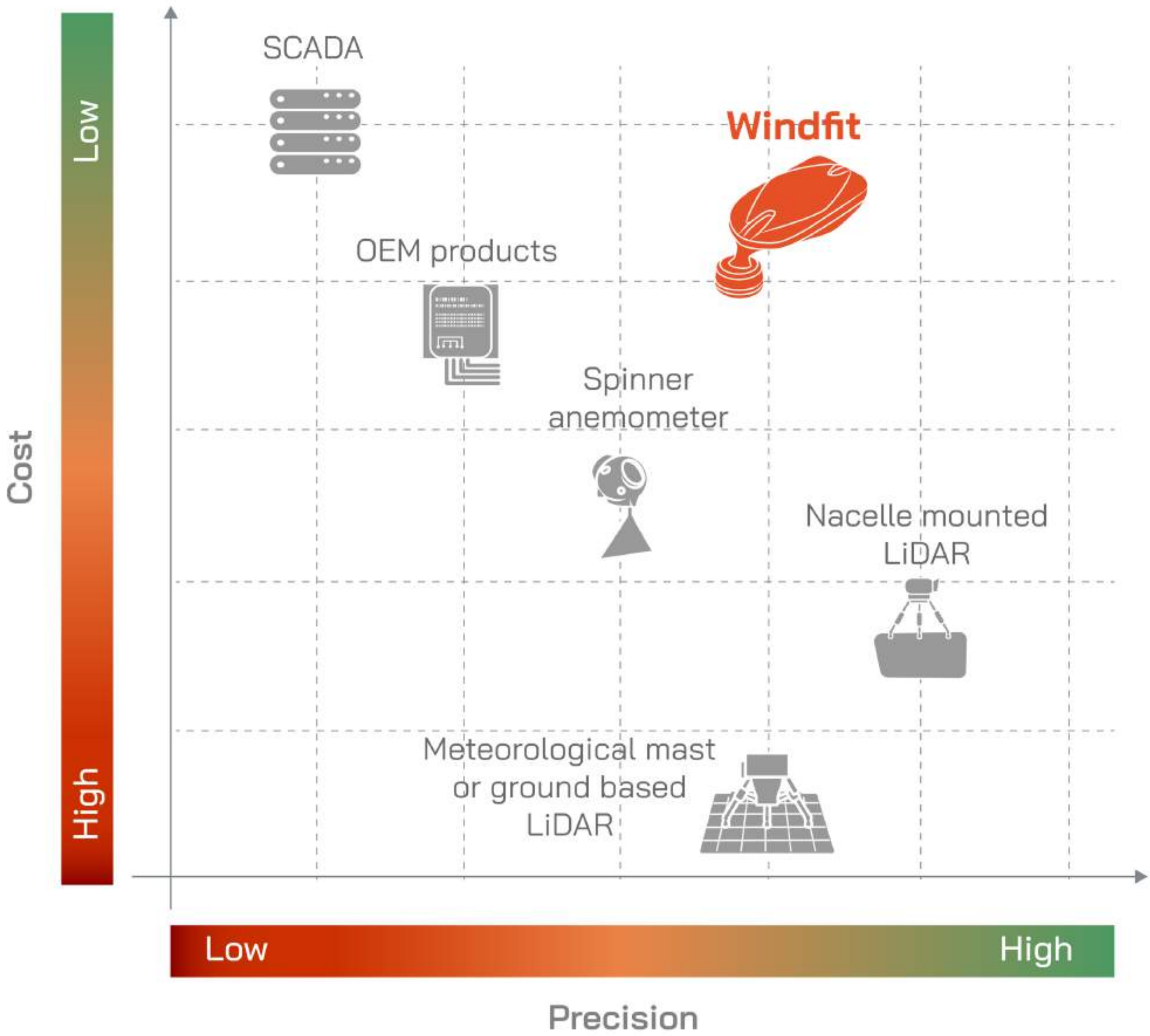
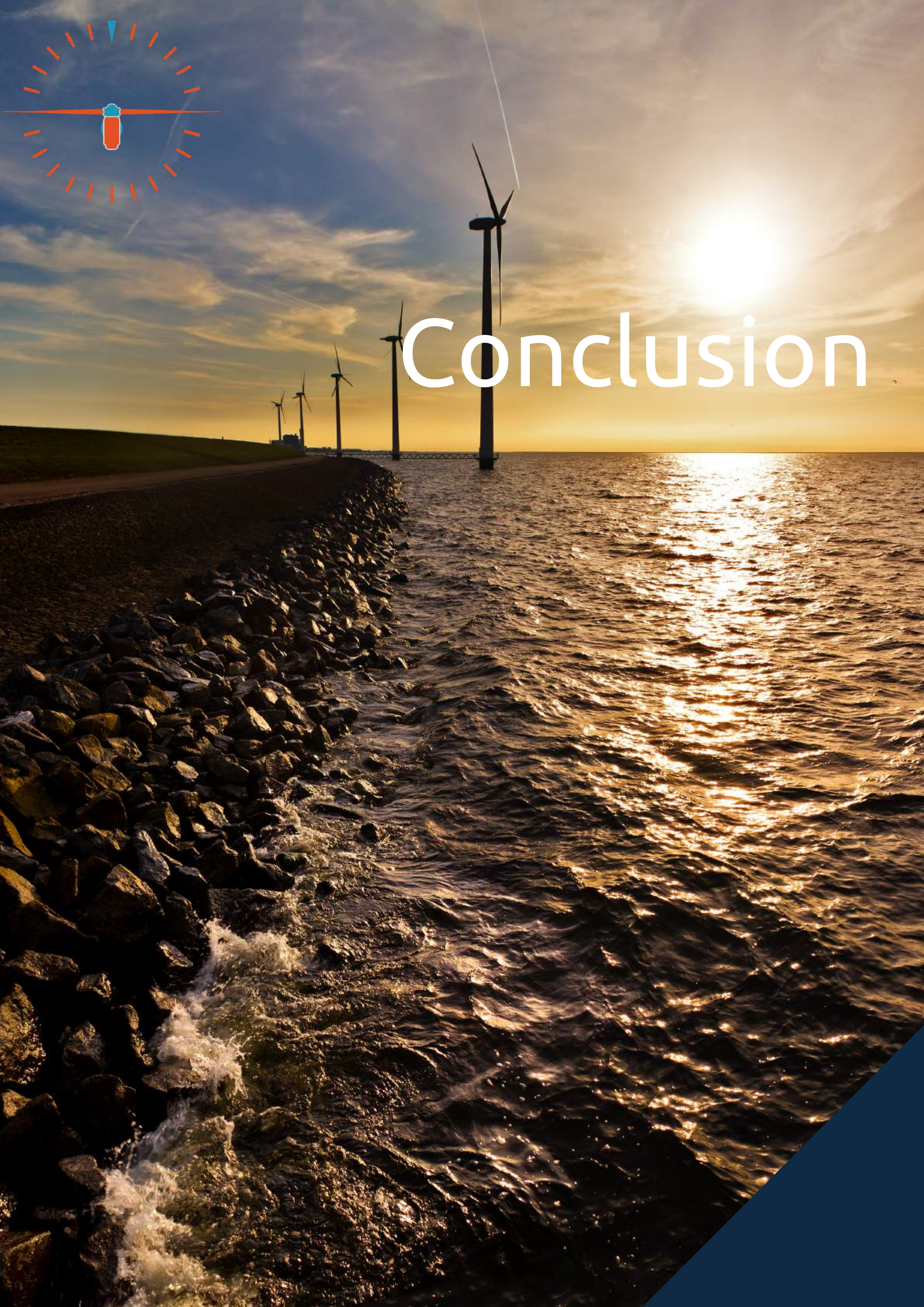


FIGURE 7. COST VS PRECISION COMPARISON OF TRADITIONAL VS NOVEL TECHNIQUE.

Conclusion



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Wind turbine yaw misalignment has grown in popularity during the last decade as one of the **key performance pitfalls of modern turbines.** On this paper this issue has been investigated in detail, discussing its impact on turbine performance and lifetime.
A review of current technologies to detect and monitor yaw misalignments has been presented, along with the introduction of a novel technique that uses a combination of independent and high frequency data measurements. Multiple advantages are observed, proving this new approach to be more cost effective than traditional methods for the continuous monitoring of wind turbine yaw misalignments.

As the wind industry continues to mature and wind turbines continue to grow in size, performance issues like yaw misalignment will become increasingly relevant. Digital solutions such as the one presented on this whitepaper will not only have implications on the performance of wind turbines, but are actually key enablers of the future challenges and developments that the wind industry is facing in the years to come, such as active wake control, system hybridization and fleet wide optimisation.

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