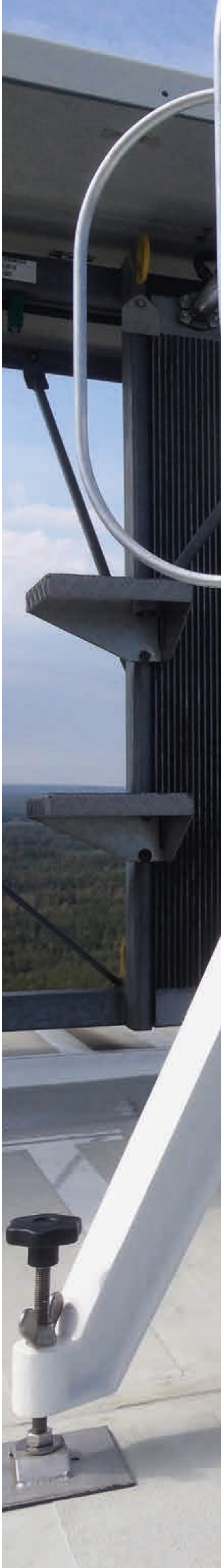
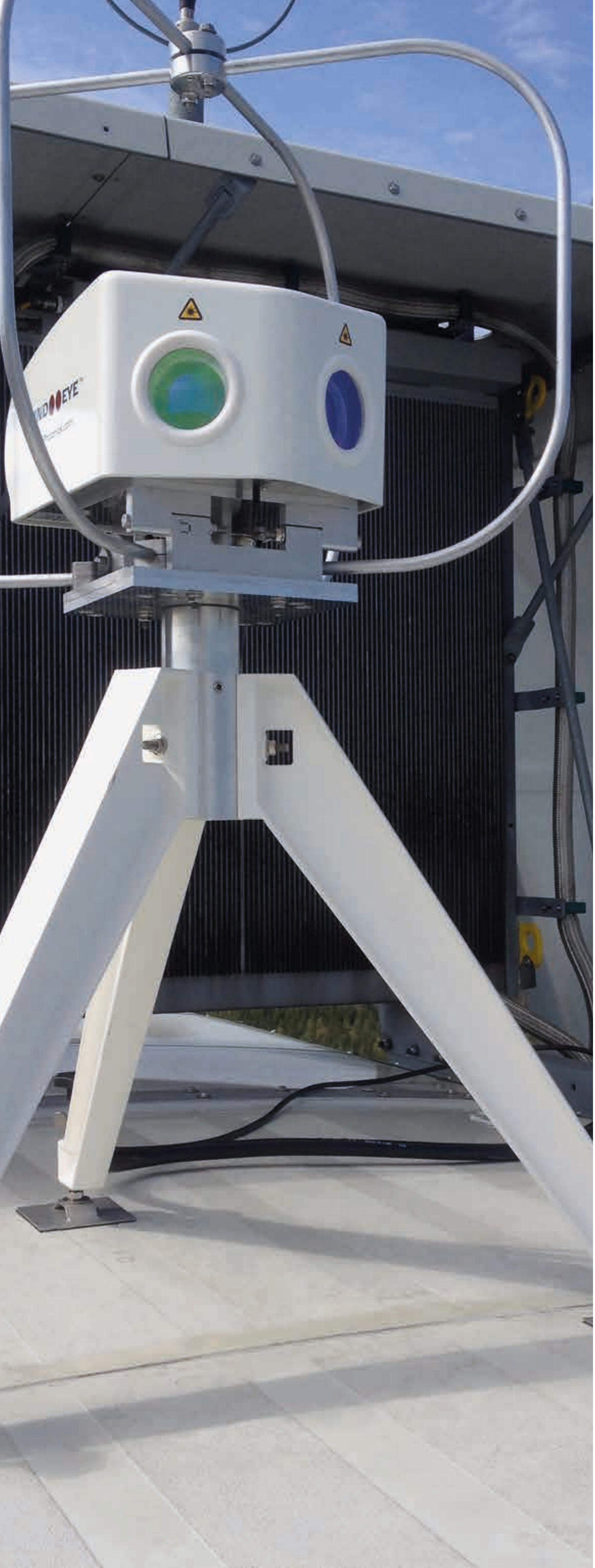
WINDAR PHOTONICS

*"Imagine being able to predict the wind..."*

# CONTENTS





***Windar Photonics offers LiDAR based optimisation solutions to the wind energy industry, allowing utilities and OEMs to increase the energy production of their wind turbines and at the same time reduce maintenance costs. Our LiDARs, which are permanently installed on the nacelle, ensure increases to AEP by 1-4% and a substantial reduction of loads through correct alignment of the wind turbine.***

# INTRODUCTION

The future of energy production invariably includes a significant contribution by renewable energy sources. Innovation and creative thinking have helped wind energy mature to its current state, which nobody could have imagined 30 years ago. That is not to say that wind energy does not still have its challenges today. Changing energy tariffs requires wind energy to be even more efficient and competitive compared with other sources of energy, if wind energy truly is to be the stable of energy production of tomorrow.

To accommodate this increase in efficiency and competitiveness, Windar Photonics has developed a remote sensor system based on LiDAR technology that measures the wind in front of the turbine, leaving the wind turbine ample time to adjust before the oncoming wind reaches the blades. Ultimately, the Windar Photonics LiDARs will help reduce loads on the turbine and increase AEP.

It is our hope you will take the time to leaf through this book and consider the benefits and advantages of being able to predict the wind.

**2005**
Initial LiDAR research within DTU

**2006**
OPDI and DTU enter into a semiconductor based LiDAR development project

**2008**
First LiDAR system developed and patent filed

**2008**
Windar Photonics A/S established, IP rights acquired from OPDI

**2010**
Proof of concept made in co-operation with DTU

**2011**
Polarisation system developed, second patent filed

2005 — 2006 — 2008 — 2010 — 2011

# WINDAR PHOTONICS

**Windar Photonics is a spin off company from the DTU Risø research environment, where the basic blueprint for the cost efficient LiDAR technology was initially conceived in 2005.**

**Windar Photonics first saw the light of day in 2008. Currently, Windar Photonics has done more than 200 installations of the Windar Photonics LiDAR optimisation solution around the globe. Likewise, Windar Photonics has**

**2012**
First installation on a Vestas V47 wind turbine

5 employees

**2013**
Commercial launch

9 employees

**2013**
Test-phases with OEMs 1.5MW, 2MW, 3.6MW, 6MW and utility companies

**2014**
Advanced installation and beam scanning technology patents filed

Windar Photonics plc established

**2014**
Initiated development of 4-beam

17 employees

**2015**
30 employees

Local offices in China, US, Canada, Spain

**2015**
London Stock Exchange AIM

New facilities

More than 130 installations worldwide

A global network of distributors for Windar's products was established

**2016**
Commercial launch of the 4-beam WindVISION™ LiDAR

More than 200 installations worldwide

2012 · 2013 · 2014 · 2015 · 2016

**established both sales and technical representation in the EU, the US, and China, making sure our customers can get the local support they deserve. Since 2008, the number of employees has increased from 3 to 30, covering R&D, assembly, management, sales and technical support.**

**In 2014, Windar Photonics was established as a PLC in the UK and listed on the Stock Exchange of London AIM in 2015.**

# THE MARKET

**Due to constant changes to power tariffs and government subsidies, the market, for both OEMs and utilities, is starting to formulate new requirements for wind energy production:**

- **Price productivity demands are increasing**
- **Minimising the Cost of Energy**
- **More AEP with limited investments and high ROI**
- **Reduced loads and increased lifetime of assets**
- **Reduced maintenance costs**

# CURRENT STATE OF WIND ENERGY PRODUCTION

Wind energy has technologically matured tremendously during the last decades. Nonetheless, there are still easily obtained advantages to be gained by embracing new knowledge and technology.

## What you know today

- How to operate turbines in different environments and under different conditions
- How to provide power curve verification according to the customer's requirements
- How to operate turbines by means of existing wind sensors and by using advanced transfer functions and algorithms
- How to offer optimisation to your customers in terms of power upgrades

## What you do NOT know today

- How to predict wind speed and wind direction IN FRONT of the turbine
- How to detect gusts and wind shear
- How to detect if the turbine is facing the de facto direction of the wind

## What you could gain if you knew more about the above

- How to increase asset longevity and reduce the overall fatigue and loads on the turbine through wake, shear, gust, and turbulence detection.
- How to increase the AEP by adjusting the turbine in relation to the direction of the wind
- How to increase the AEP by optimising your pitch control and by adding anticipatory pitch functions

# MISCONCEPTIONS CONCERNING WINDAR PHOTONICS' LIDAR TECHNOLOGY

### *"Yes we have tried LiDAR technology before – we know it works – but the prices are way too high"*

- The Windar Photonics LiDAR is developed ONLY as a nacelle-based LiDAR with low cost and durability in mind
- Priced 80% lower than conventional LiDAR systems
- Immediate payback from day one due to load reductions and increased power production
- We constantly aim to offer OUR customers the lowest price possible – year after year

### *"Yes LiDARs can predict wind speed and wind direction – but data availability is often too inadequate"*

- We had the same challenges two years ago. Since then we have been working intensively on improving the data availability to a near perfect state
- Availability is on average 95% or more – even in conditions with rain or light snowfall
- Improvements are constantly being added to the system and future software upgrades are of course provided free of charge and can be implemented remotely

### *“Yes, we use LiDAR for ground-based site assessment and it works - but such an advanced system will not work in the harsh environment on top of a wind turbine”*

- The Windar Photonics LiDAR is designed and built to be mounted on top of a wind turbine. We have invested in our own climate and salt chambers, allowing us to constantly verify the durability and performance of the LiDAR system
- Tested and improved in order to meet OEMs‘ internal requirements for wind sensors
- We have NO mechanical or moving components and OUR system requires very little maintenance
- We have done more than 200 installations worldwide - on various turbines in diverse climates. This extensive experience has helped perfect the data availability of the system in almost all weather conditions

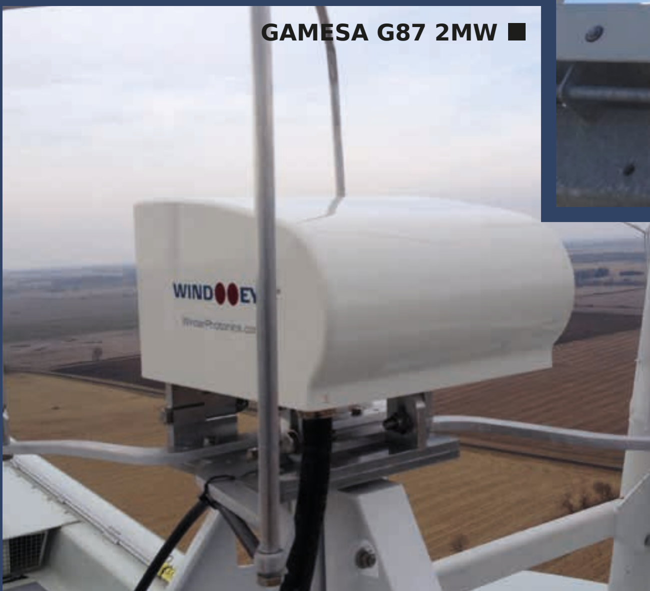
### *“A LiDAR might work for us, but we can do the same without a LiDAR by optimising our software programs and fine tuning our control systems”*

- We do not question this at all, however our tests on similar turbines show a large improvement and tangible advantages by using Windar‘s LiDAR
- Measurements utilising conventional wind sensors requires complex algorithms, depends on site conditions, and often varies from wind farm to wind farm – due to A LOT of different transfer functions
- A LiDAR requires NO transfer function and can be used universally for all wind farms

## *Additional References*


■ SIEMENS 3.6MW


■ ENVISION 3.6MW


GAMESA G87 2MW ■


■ GAMESA G87 2MW


■ GE 1.5MW


■ VESTAS V80 2MW


■ GE 1.5MW

SENVION 2MW

NORDEX 2.5MW

VESTAS V90 2MW

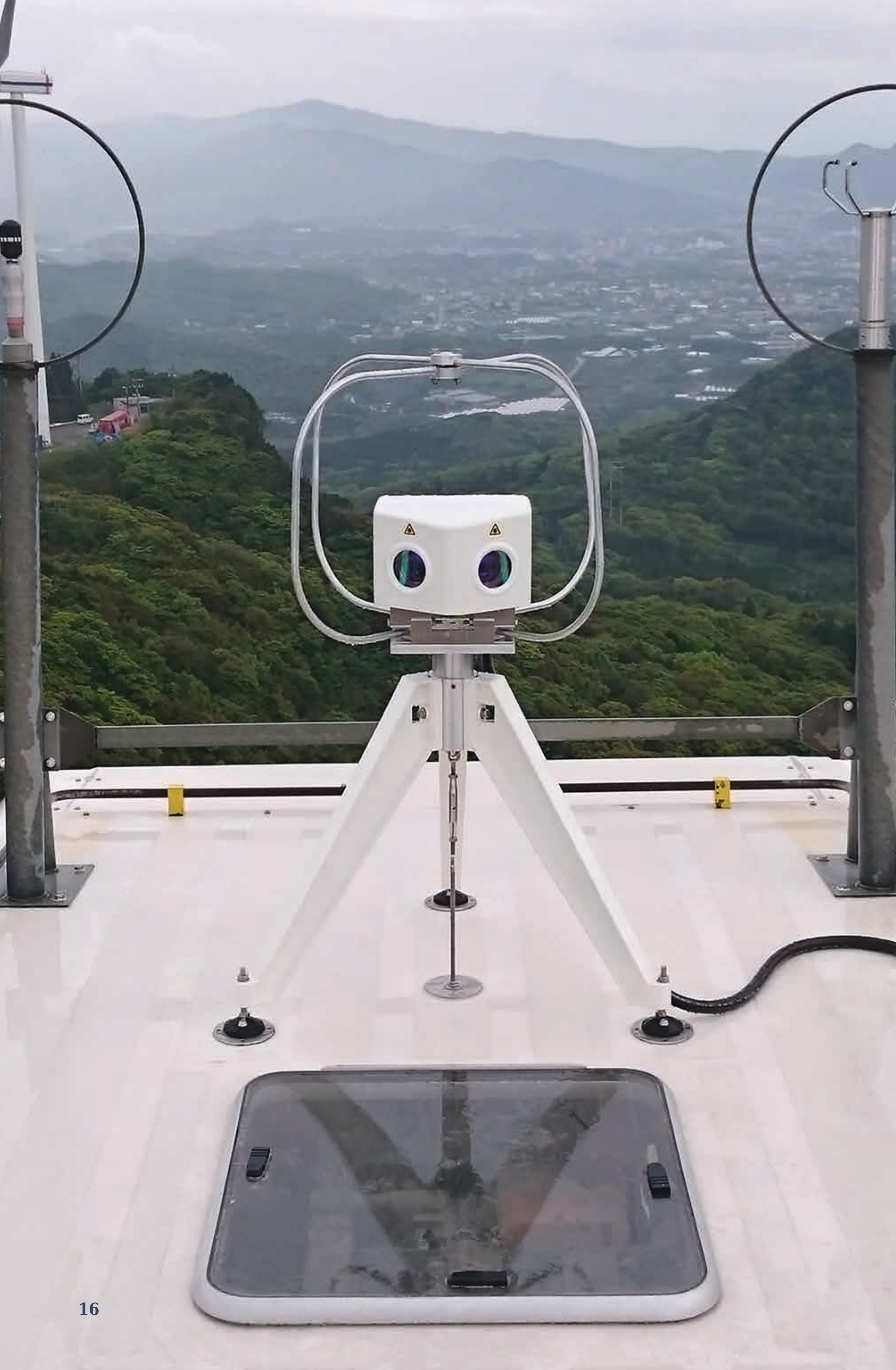
NEG MICON NM82 1.5MW

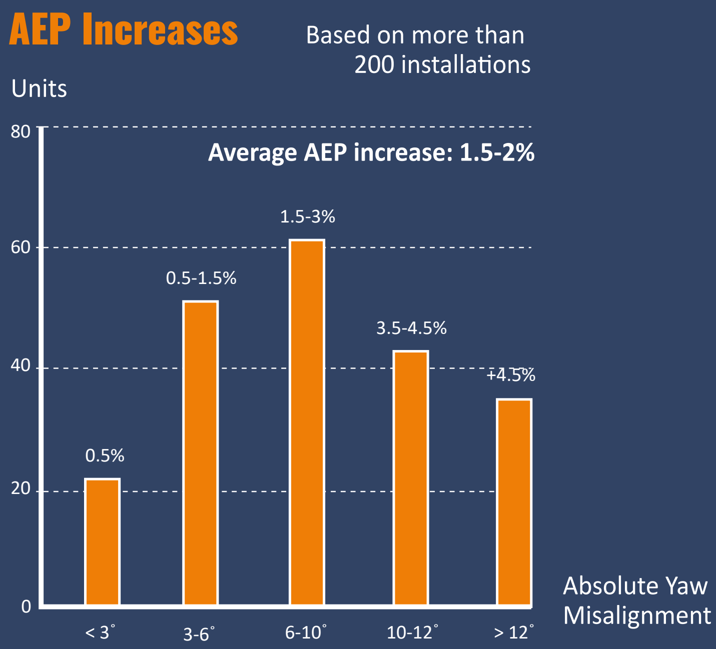
VESTAS V100 1.8MW

VESTAS V90 1.8MW

VESTAS V80 2MW

GAMESA G80 2MW






# REFERENCES

**VESTAS –** V47, V66, V80, V82, V90, V100, V112

**NORDEX –** N90

**ENVISION –** 3.6MW, 4MW

**SIEMENS –** 2.3MW, 3MW, 3.6MW, 4MW, 6MW

**GAMESA –** 2MW

**SUZLON –** 2.1MW

**GE –** 1.5MW, 1.7MW, 2.75MW

**NEG-MICON –** 0.6MW, 1.65MW

**SENVION –** 2MW

**UNITED POWER –** 3MW

**LAGERWEY –** 0.9MW

**WINDEY –** 0.75MW

**SINOVEL –** 1.5MW

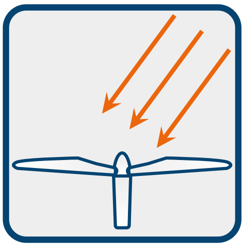
**CSIC –** 2MW

**DONGQI –** 1.5MW

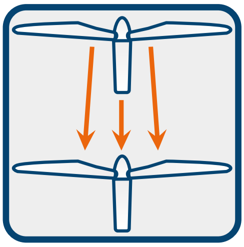
**CLIPPER –** 2.5MW

# TECHNOLOGY OVERVIEW

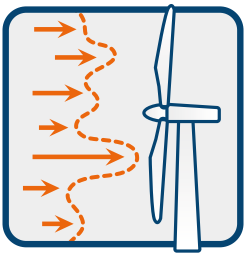
***Wind turbines today are in general technologically advanced and efficient. However, that is not to say that there is not room for improvements and new improved solutions to old problems. Windar Photonics has tried to address some of the key areas, where we think our technology and products can make an appreciable difference for both the OEM and the wind turbine owner.***



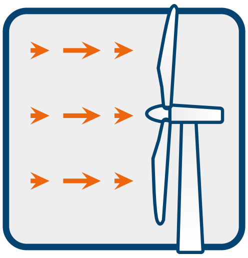
**Yaw Correction**



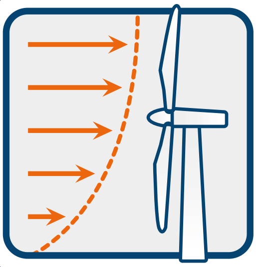
**Wake Detection**



**Turbulence Detection**



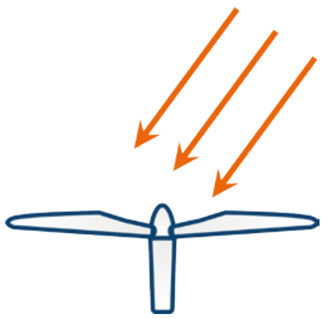
**Gust Detection**



**Shear Detection**

## Yaw Correction

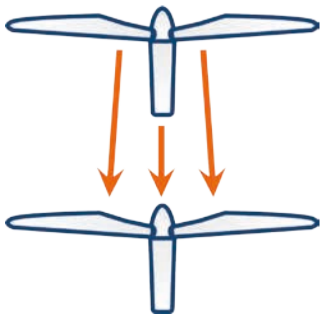
Most turbines have some degree of yaw misalignment, which results in the turbine being subject to potentially damaging loads and a sub-optimal energy production. Normally, the wind sensors measure the wind at the turbine itself, which results in the measurements being affected by the distortion of the wind flow caused by the turbine itself. As such, the ordinary wind sensors constitute a reactive system that accounts for the wind after it has passed.



The Windar Photonics LiDAR, on the other hand, is a wind sensor that actively measures 80m in front of the turbine. These measurements form the basis for the calculations that the system performs, which can be used to predict the wind speed and wind direction. These measurements and calculations can thus be supplied to the wind turbine controller, making it possible for the turbine to adjust according to the oncoming wind. Since the LiDAR measures continuously, it is possible to continuously adjust any potential yaw misalignment as well.

## Wake Detection

Wake situations can be caused by several conditions relating to the wind turbine's environment – including natural topographical obstacles. In a wind farm, wake is mostly caused by the distortion of the wind flow from nearby wind turbines.

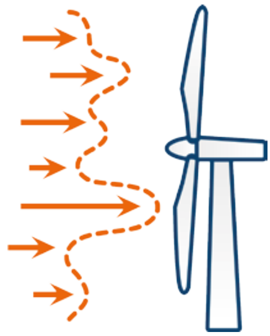


If the LiDAR is installed on a turbine that is being affected by wake, the measurements will not be representative of the de facto wind speed and wind direction, and hence the turbine will not be able to adjust correctly in relation to the wind, resulting in a loss of power and increased loads on the turbine.
To prevent the consequences of a turbine being subject to wake situations, the LiDAR is able to detect wake

situations and prevent the turbine from adjusting according to the faulty measurements.

The LiDAR measures wake by tracking the changes in the signal shape between the beams over time, which allows the system to detect homogeneity. If there is a difference from one beam to the other, then the flow is not homogeneous and there will be a potential wake situation, which can subsuquently be avoided by changing the control behaviour of the turbine.

## Turbulence Detection

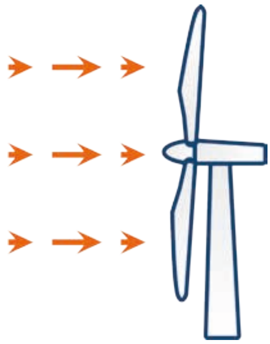


Turbulence is an unavoidable meteorological factor caused by the processes of the atmosphere, which can be hard to predict in relation to the optimal operation of a wind turbine.

Turbulence intensity can be derived from the LiDAR's measurements, which is calculated as the standard deviation from the mean measurement of a signal. As such, the system can derive the intensity factor from each beam or average out the intensity factor for both beams.

Utilising complex algorithms, the LiDAR is able to detect turbulence and store the data for later analysis. The data, along with a LiDAR specific guideline concerning the processing and analysis of the data, can provide a basis for further load-optimisation of the turbine by the wind turbine owner.

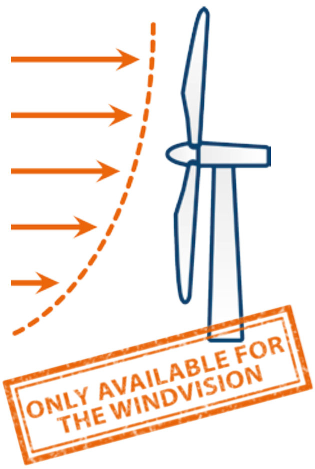
## Gust Detection



Gust are essentially substantial variations in wind speed, where the wind speed suddenly increases before reaching the turbine. The problem occurs when the sped up wind reaches the turbine, which causes the rotor to go into over-spin, resulting in both increased loads on the turbine and causing the power production to spike above the rated level – essentially losing the extra energy from the over-spin.

Furthermore, gust detection can help to enhance the energy production in low wind areas, where the energy production typically benefits from turbines with an extended rotor diameter. The gust detection will allow for an extended rotor diameter along with the possibility of saving on tower construction costs, as the turbine will be subject to significantly reduced loads.

All the Windar Photonics LiDARs can perform gust detection, recording the data for later loads optimisation. If the WindEYE™ is integrated from the design stage of the turbine, the WindEYE™ will be able to use its anticipatory pitch function that allows the turbine to pitch prior to the gust reaching the turbine, effectively mitigating the power spike and the increase in loads.




## Shear Detection

The phenomenon of shear occurs when the wind speed varies significantly at different altitudes, causing the wind turbine rotor to be subject to vastly different oncoming wind speeds, which will cause even more strain on the turbine in general and specifically on the rotor and the gearbox.

Due to the WindVISION™ system's ability to measure the wind speed at various altitudes, the system is able to detect shear, which can subsequently be corrected through the turbines controller. Ultimately, the shear detection gives the wind turbine owner the option to significantly reduce the loads on the turbine caused by the wind shear.


Tektronix


# REASONS TO WORK WITH WINDAR PHOTONICS

It is our ambition to enhance the longevity of our customer's assets by lending our expertise and knowledge of LiDARs and wind turbine design, which makes the installation and application easy and uncomplicated for our customers.

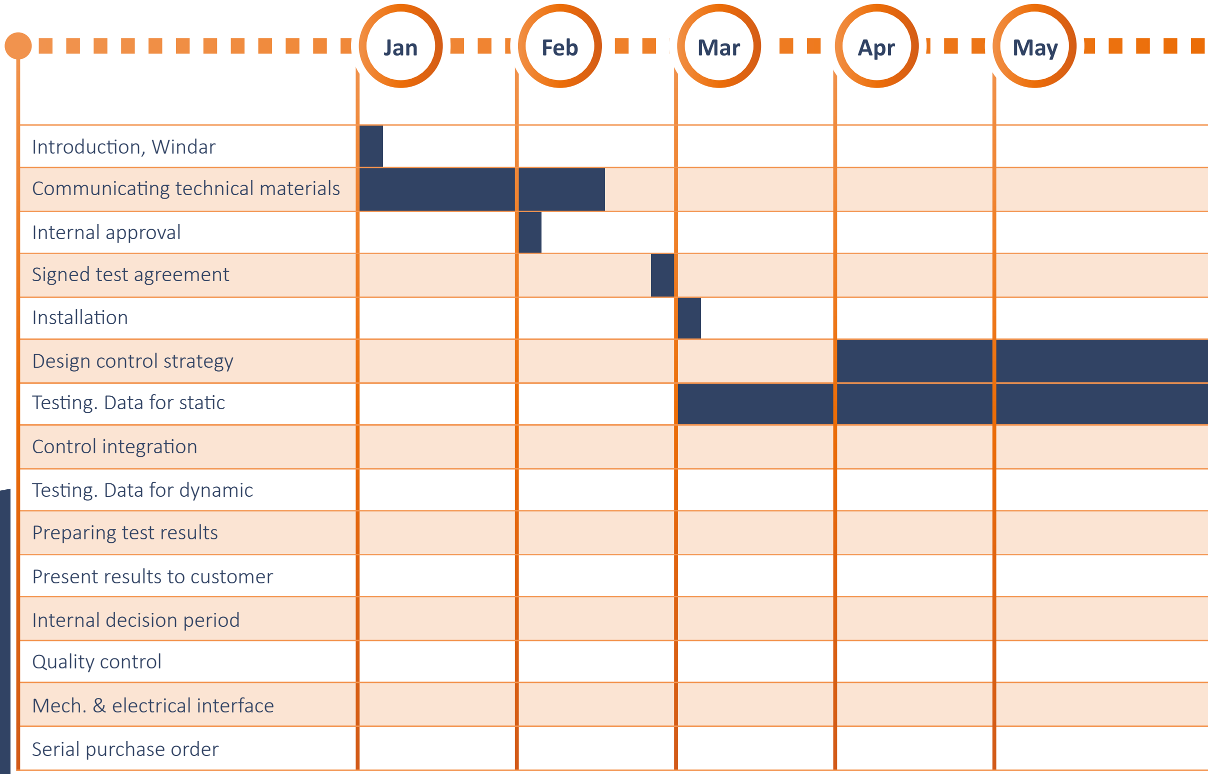
## Product-wise

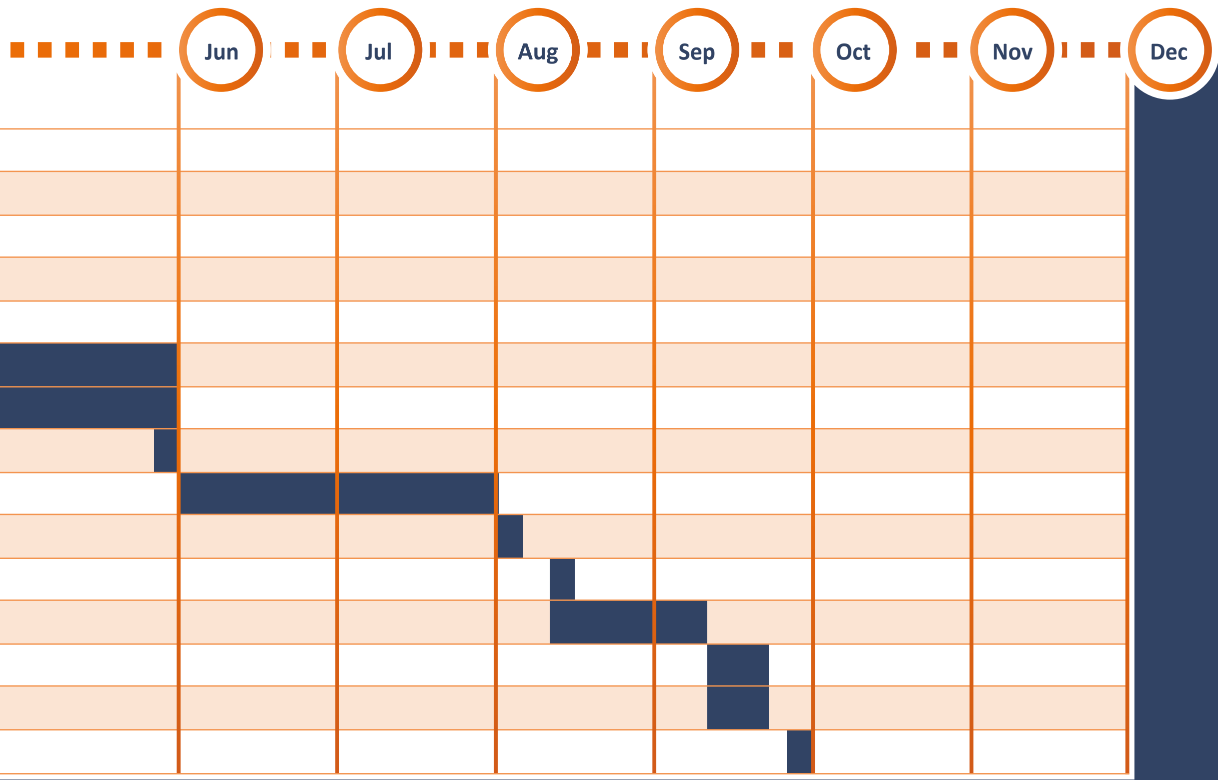
- Latest and most modern sensor technology in the wind industry
- Reduced loads and fatigue on bearings, blades, and gearbox, due to wake, shear, gust and turbulence detection
- Increased power output for customers by min. 1-4%
- Improved yaw optimisation and enhanced pitch performance
- Option to increase the rotor diameter due to reductions of both peak and fatigue loads
- Possibility to work with anticipatory pitch control and reduce power spikes

## Company-wise

- Listed company on the London Stock Exchange AIM – WPHO
- Extensive experience within the wind industry
- Extensive knowledge of control optimisation
- Aiming for large volumes and reduced cost prices

# PLAN FOR IMPLEMENTATION

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# PRODUCTS


WINDVISION™


WINDEYE™

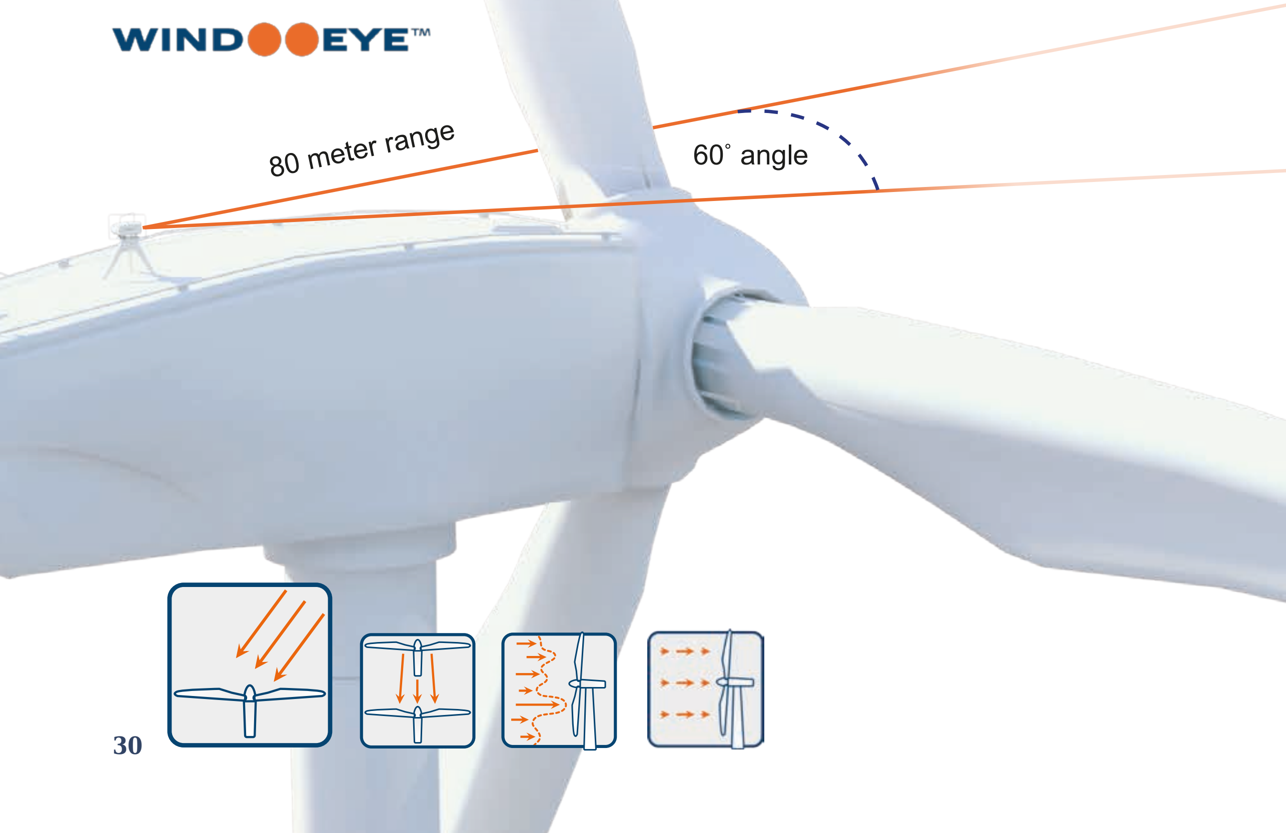
# WINDEYE™

## Gain more power

The WindEYE™ optimises the wind turbine by correcting yaw misalignment, which can potentially increase the AEP by 1.5% to 2% on average - and in some cases even by as much as 4%. Correcting the yaw misalignment will further result in a mitigation of damaging loads on the turbine, enhancing the lifespan and uptime of the wind turbine.

To enable the dynamic yaw correction feature of the WindEYE™, the LiDAR needs to be integrated with the wind turbine controller at the design stage. Alternatively, the WindEYE™ can be integrated by means of the WindTIMIZER, which acts as a data converter between the LiDAR unit and the control system.

The AEP increase provides payback times within 12-36 months - depending on the local energy tariffs, while the reduced loads ensure that the assets are stable producers for years to come.

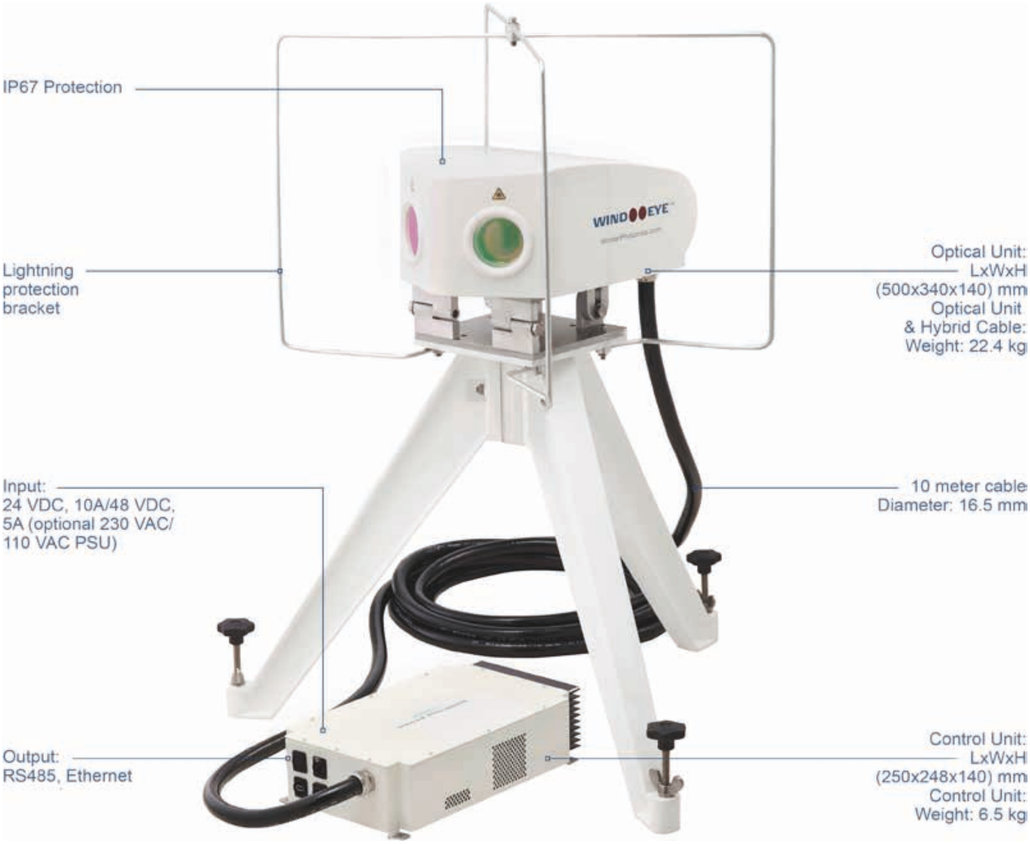


## Cost efficient LiDAR solution

- AEP increases by 1-4%, 1.5% on average
- Dynamic yaw misalignment correction
- Reduces maintenance requirements
- Increases the lifetime of the turbine
- Reduces loads on the turbine
- Wake detection

## Features

- No moving mechanical parts
- Only requires a minimum of maintenance
- Easy handling and installation
- A light-weight and compact system
- Durable design

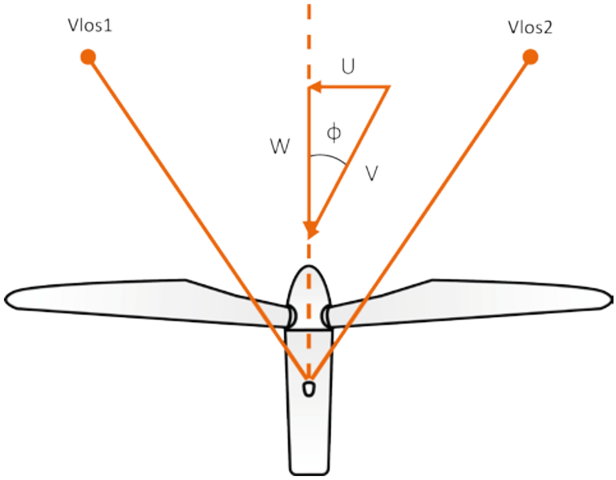



## Technical data

| | |
|---|---|
| **Laser source** | Continuous Wave Laser,<br>Laser Source, Eye safety class 4M<br>LiDAR system Eye safety class 1M |
| **Wind speed range** | 2 m/s - 75 m/s |
| **Data output rate** | 1 Hz (2Hz optional) |
| **Operating temperature** | -40°C to +55 °C |
| **Physical interfaces** | RS485, Ethernet |
| **Dimensions** | Optical Unit: 500 mm x 340 mm x 140 mm (L x W x H)<br>Control Unit: 250 mm x 248 mm x 140 mm (L x W x H) |
| **Weight** | Control Unit: 6.5 kg<br>Optical Unit & Hybrid Cable: 22.4 kg<br>Optional Tripod: 9.8 kg |
| **Cable** | Length 10 m. Diameter 16.5 mm |
| **IP Class, Control Unit** | IP67 |
| **IP Class, Optical head** | IP67 |
| **Power supply** | 24 VDC, 10A / 48 VDC, 5A (optional 230 VAC /110 VAC PSU) |
| **Data storage** | 12 Months |

## Protocol and Data

The general concept behind the WindEYE™ LiDAR's measurements is displayed in the below diagram:

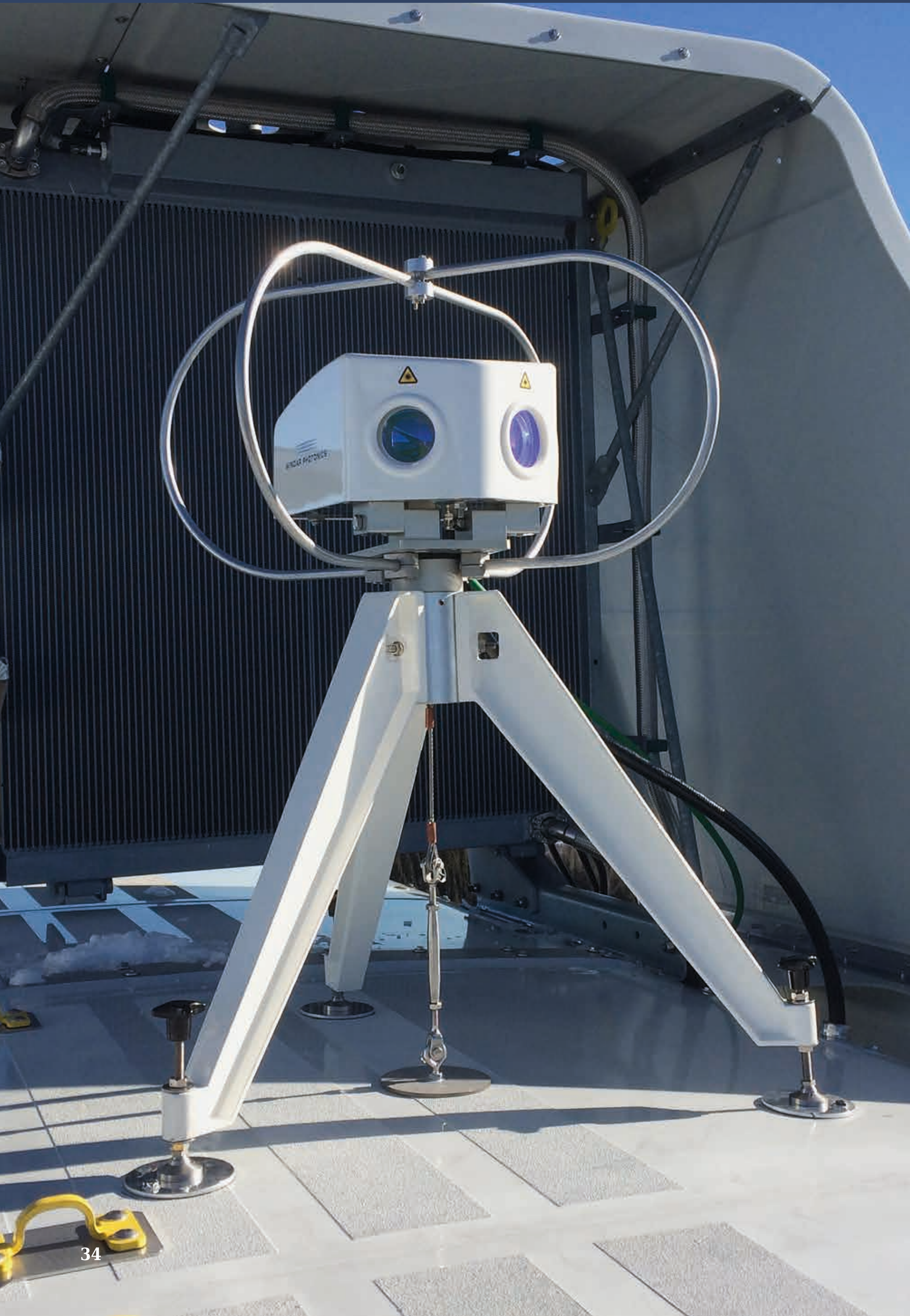



The measurements and calculations will be collected and stored in an accessible ASCII format in accordance with the below protocol list:

| Protocol list from RS485 | | |
|---|---|---|
| **Protocol** | **Specification** | **Unit** |
| **Timestamp** | | YYYY/MM/DD HH:MM:SS |
| **Vlos1** | Measured Wind speed along beam 1 | Cm/s |
| **Vlos2** | Measured Wind speed along beam 2 | Cm/s |
| **U** | Calculated Lateral Wind speed | Cm/s |
| **W** | Calculated Axial Wind speed | Cm/s |
| **V** | Calculated Incoming Wind speed | Cm/s |
| **Phi (Φ)** | Calculated Misalignment angle | °x100 |
| **Status** | 1 second measurement Status | 0/1 – Bad/Good |

*An example of data from the WindEYE™*

| Timestamp | Vlos1 | Vlos2 | U | W | V | Phi | Status |
|---|---|---|---|---|---|---|---|
| 2014-01-27 13:06:50 | 1044 | 866 | 178 | 1102 | 1117 | 917 | 1 |
| 2014-01-27 13:06:51 | 1047 | 895 | 152 | 1121 | 1131 | 772 | 1 |
| 2014-01-27 13:06:52 | 1016 | 826 | 190 | 1063 | 1080 | 1013 | 1 |
| 2014-01-27 13:06:53 | 1051 | 785 | 266 | 1060 | 1092 | 1409 | 0 |
| 2014-01-27 13:06:54 | 1055 | 783 | 272 | 1061 | 1095 | 1438 | 1 |
| 2014-01-27 13:06:55 | 980 | 768 | 212 | 1009 | 1031 | 1186 | 1 |
| 2014-01-27 13:06:56 | 965 | 723 | 242 | 974 | 1004 | 1395 | 1 |
| 2014-01-27 13:06:57 | 952 | 756 | 196 | 986 | 1005 | 1124 | 1 |
| 2014-01-27 13:07:00 | 958 | 709 | 249 | 962 | 994 | 1451 | 1 |
| 2014-01-27 13:07:01 | 954 | 776 | 178 | 998 | 1014 | 1010 | 1 |
| 2014-01-27 13:07:02 | 952 | 751 | 201 | 983 | 1003 | 1155 | 1 |



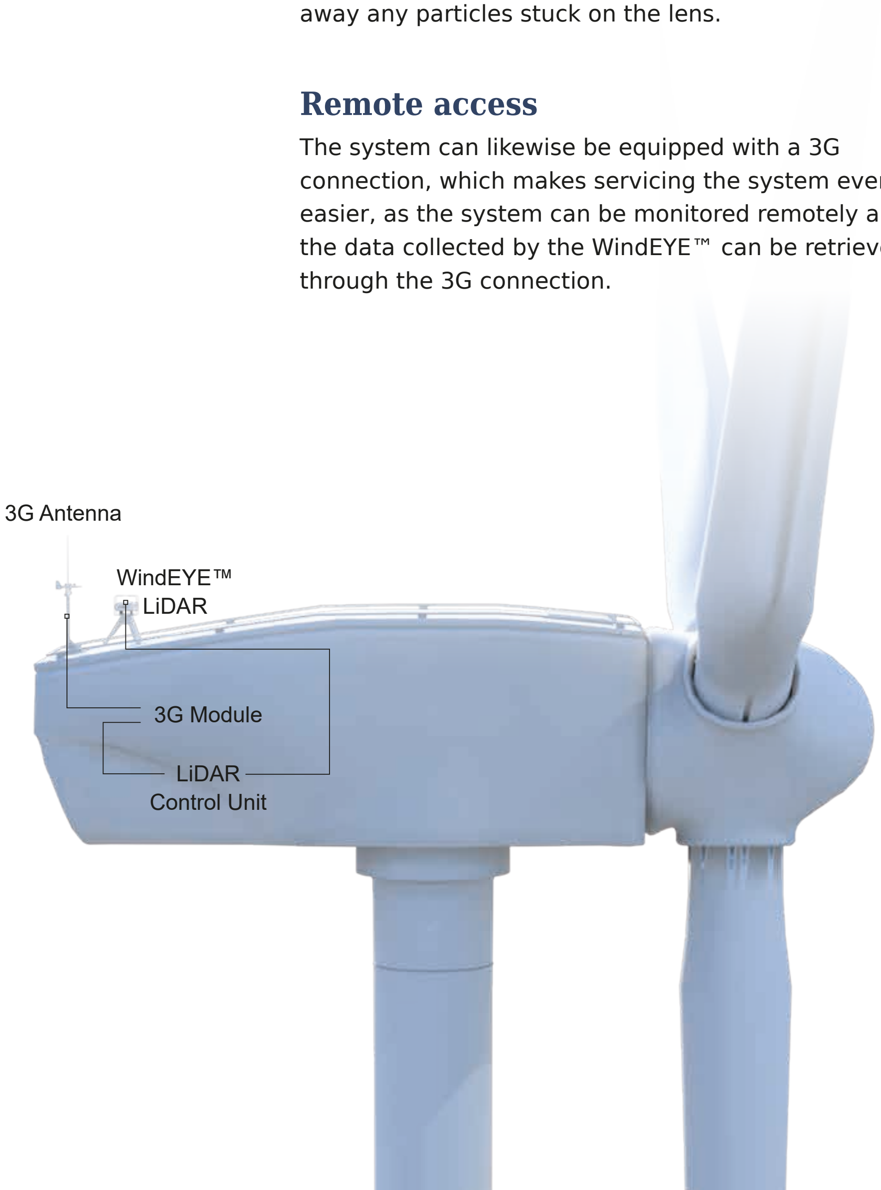
## Maintenance

The system does not contain any moving or mechanical parts, which can be worn out or otherwise be subject to wear and tear. As such, the most maintenance-heavy aspect of the system is the light source, which will have to be replaced once every two years. Luckily, this very easy process can coincide with the normal service and maintenance of the turbine.

The environment atop the nacelle is both harsh and unclean. Due to the operational environment of the WindEYE™, the lenses on the WindEYE™ have been designed to resist dirt and dust. The LiDAR will operate flawlessly even with significant amounts of dirt on the lenses without interfering with the signal. Furthermore, the design of the lenses allows natural rainfall to wash away any particles stuck on the lens.

## Remote access

The system can likewise be equipped with a 3G connection, which makes servicing the system even easier, as the system can be monitored remotely and the data collected by the WindEYE™ can be retrieved through the 3G connection.



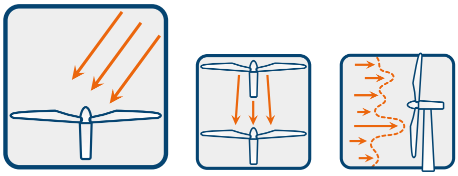
# WINDEYE™ & WINDTIMIZER SYSTEM

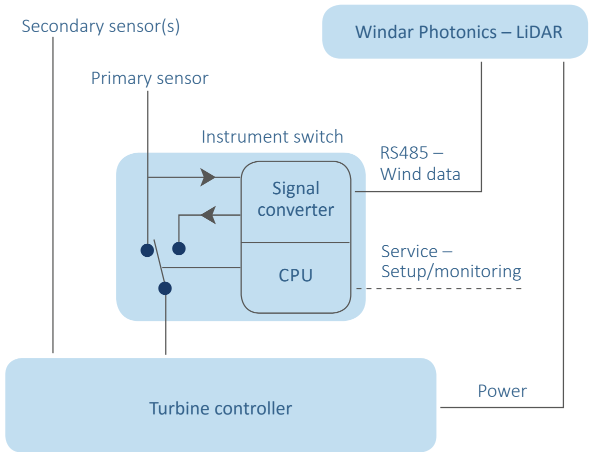

## Control integration with the WindTIMIZER for dynamic yaw-misalignment correction

To facilitate a dynamic and continuous yaw-misalignment correction, it is required that the Windar Photonics WindEYE™ optimisation solution is integrated with the wind turbine controller. The WindTIMIZER is Windar Photonics' elegant solution to facilitate the integration between the WindEYE™ system and the wind turbine controller, where the WindTIMIZER functions as a mediator between the controller and the WindEYE™ system without the necessity of actually altering anything in the wind turbine controller at all.

## Integration and signal conversion

The WindTIMIZER receives the signals from both the legacy wind-sensors and the WindEYE™ system, converts the signal from the WindEYE™ system to the protocol of the legacy wind-sensor signals, and sends the signal of the WindEYE™ system into the wind turbine controller, as long as the WindEYE™ system signal is available. This makes the WindEYE™ instrument "appear" as the legacy anemometry to the wind turbine control system, which makes it possible to integrate the WindEYE™ without any changes to the wind turbine control system. Furthermore, the WindTIMIZER will compare the converted measurements from both the WindEYE™ system and the legacy anemometry to check for any faults. In case the WindEYE™ system gets an unusable datum (e.g. if a blade passes in front of one of the WindEYE™'s beams),






then the WindTIMIZER will be able to use the datum from the legacy sensor instead. A diagram showing the software system of the WindTIMIZER and the conversion process can be seen in figure 1.

## Safety chain

Maintaining the wind turbine safety chain is of the greatest importance, hence it is imperative that any technical or metereological problems involving the WindEYE™ system and the WindTIMIZER do not jeopardize the integrity of the safety chain. In case of a force majeure emergency, like a lightning strike that harms the WindTIMIZER, a failsafe switch will still transmit the legacy anemometry signal to the controller.

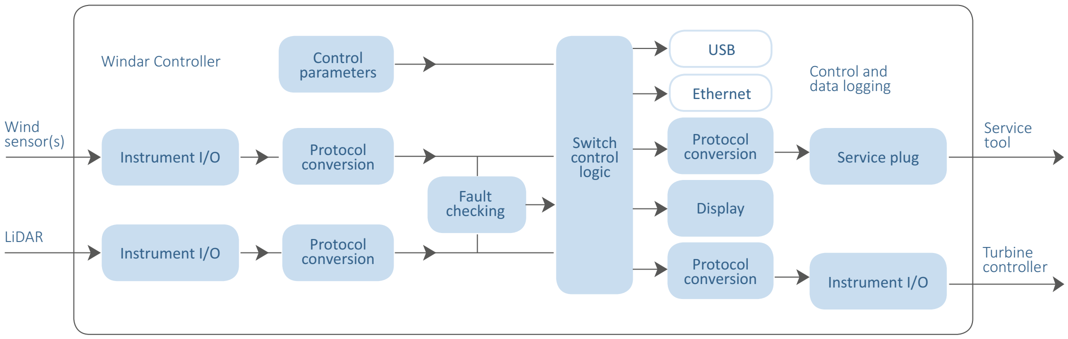



*Figure 1*

# WINDVISION™

## Shear detection and expanded measurement capabilities

The WindVISION™ system is the most advanced LiDAR in Windar's product portfolio. The four beams allow the LiDAR to measure in both the horizontal and the vertical planes, which enables the WindVISION™ system to deliver unmatched pitch and yaw optimisation. Precisely because of the four beams, the system is able to detect wind shear, which enables the wind turbine owner to adjust the pitching strategy of the turbine to reduce the tremendous loads generated by wind shear.

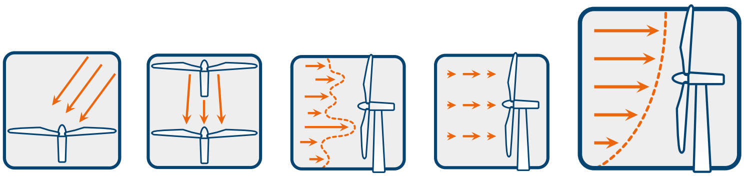
The WindVISION™ is of course also able to measure and detect yaw misalignment, wake situations, gusts, and turbulence – just like the 2-beam WindEYE™.

## Direct control integration

The intention behind the WindVISION™ is to offer a LiDAR system with expanded measurement and data collection capabilitites for OEMs and asset owners who want to have more control over the optimisation process, and an extended range of data and optimisation options available.

To accommodate the extended range of optimisation features, the WindVISION™ must be directly integrated with the wind turbine control system. As such, we recommend the WindVISION™ for more extensive projects focused on load reductions, whereas we recommend the WindEYE™ system for more straight-forward AEP optimisation applications and retrofitting.

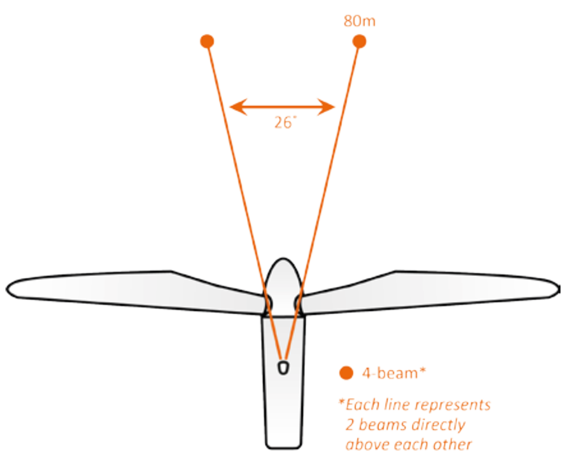
WINDVISION™

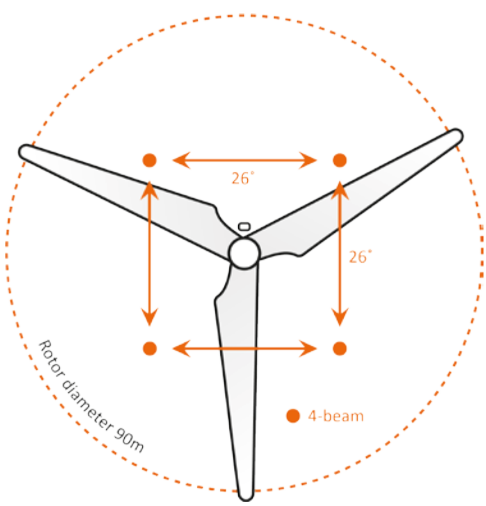


*The wind shear detection ability is exclusive to the WindVISION™ 4-beam LiDAR*

## Features

- Complete strategy for yaw and pitch optimisation
- Load reductions through wind shear detection & anticipatory pitch control
- Load reductions through wake, turbulence, and gust detection
- Increased AEP of 1-4% through yaw-misalignment correction

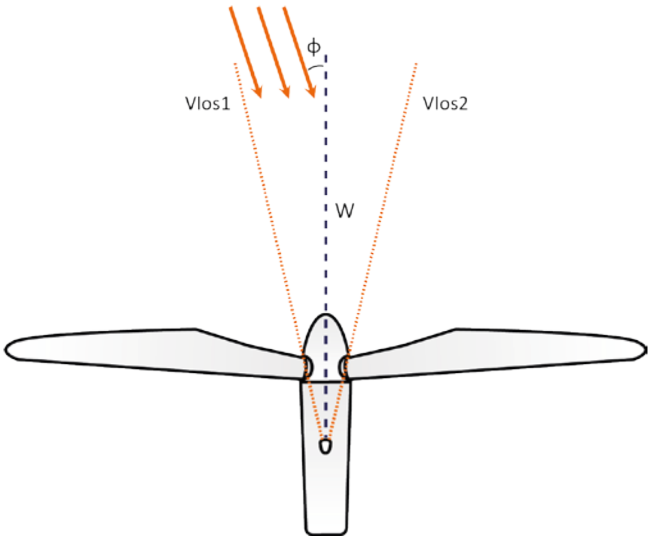



## Technical data

| | |
|---|---|
| **Laser source** | Continuous Wave Laser,<br>Laser Source, Eye safety class 4M<br>LiDAR system Eye safety class 1M |
| **Wind speed range** | 2 m/s - 75 m/s |
| **Data Output Rate** | 4 Hz. 1 full scan per 1 sec. |
| **Operating temperature** | -40°C to +55 °C |
| **Interfaces** | RS485, Ethernet |
| **Dimensions** | Optical Unit: 485 x 290 x 280 (L x W x H)<br>Control Unit: 250 mm x 248 mm x 140 mm (L x W x H) |
| **Weight** | 17 kg |
| **IP Class, Control Unit** | IP67 |
| **IP Class, Optical head** | IP67 |
| **Power supply** | 24 VDC, 10A / 48 VDC, 5A (optional 230 VAC /110 VAC PSU) |
| **Data Storage** | 12 Months |

Mechanically speaking, the system does not deviate much from the weight and size of the current two beam offering, so it is as light and durable as ever with the added benefit of including more of the electrical systems within the LiDAR head itself, which will make it even easier to handle and install.




| Protocol list from RS485 | | |
|---|---|---|
| **Protocol** | **Specification** | **Unit** |
| **Timestamp** | | YYYY/MM/DD HH:MM:SS |
| **Phi (Φ)** | Calculated Misalignment angle | °x100 |
| **Vlos1, Vlos2, Vlos3, Vlos4** | Mean wind speed measured along Vlos1-Vlos4 | Cm/s |
| **FlagInterp1-FlagInterp4** | 0: observed Vlos1-Vlos4<br>1: interpolated Vlos1-Vlos4 | 0/1 |
| **V412, V123, V234, V341** | 3D wind vector computed with Vlos1, Vlos2, Vlos3 and Vlos4 | Cm/s |
| **VeffM** | Effective wind speed at measuring plane | Cm/s |
| **VeffR** | Effective wind speed at rotor plane | Cm/s |
| **DirH** | Mean horizontal misalignment | 1/100° |
| **DirV** | Mean vertical angle of the wind | 1/100° |
| **Status** | 0: No beam measured<br>1: 1 beam measured<br>2: 2 beam measured<br>3: 3 beam measured<br>4: 4 beam measured | 0, 1, 2, 3, 4 |

# LIDAR TECHNOLOGY EXPLAINED

*On the following pages you will find a few passages relating to some of the central problems involving remote sensing equipment in general and LiDAR technology in particular.*

# WINDAR PHOTONICS' COST EFFICIENT LIDAR TECHNOLOGY EXPLAINED

Our wind sensor measures the wind by using laser light. The principle known as LiDAR (**L**ight **D**etection **A**nd **R**anging) was invented in the 1960s. We have fine-tuned the technology and replaced expensive light sources with a much more affordable laser, which allows Windar Photonics to offer our customers an inexpensive and cost-effective LiDAR system.

A wind LiDAR relies on the Doppler effect – a slight change in the frequency of the backscattered light – caused by moving air-borne particles passing through the laser beam's focus point in the atmosphere.
The Doppler frequency shift gives direct information of the wind speed component along the line-of-sight of the beam. Due to the ultra-low power levels of the typical backscatter (in the order of 1 part in ~100 billion of the transmitted laser power) associated with the lower atmospheric boundary layer, a very sensitive optical detection scheme and a relatively high powered and narrow-line width laser has to be employed. The most widely used scheme to extract Doppler shift information is the so-called "optical heterodyne detection".

## Cost-efficient LiDAR

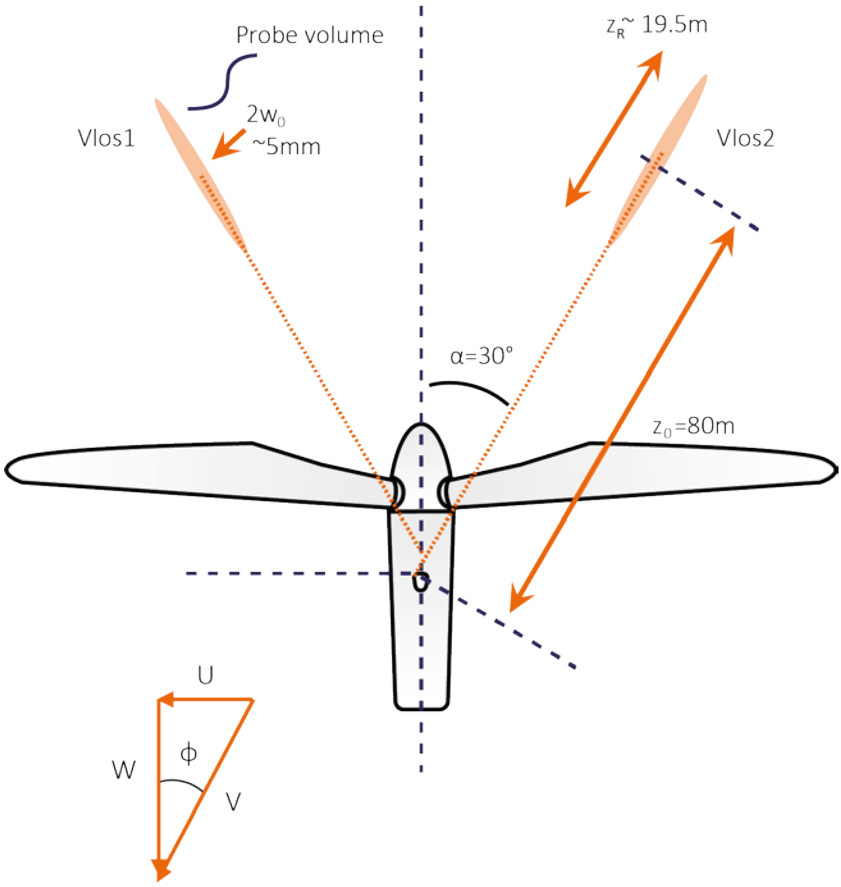
For commercial wind LiDARs, stringent eye-safety requirements have led to the preference for lasers operating near the 1532 nm wavelength. A review of the existing wind LiDAR products will show that they employ expensive fiber laser and/or fiber amplifier technologies to achieve the required laser output power and linewidth at 1550 nm operation.

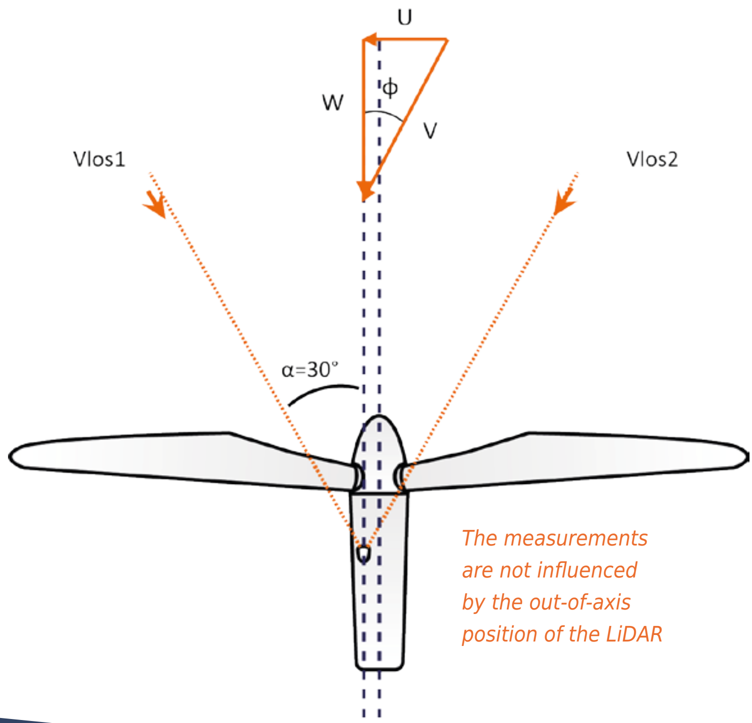
A previous study has found that up to 25% of the total system cost can be attributed to such laser sources alone. Windar Photonics‘ aim is to deliver cost efficient LiDAR systems for wind velocity sensing by using more affordable and compact lasers (at 1550 nm), which in conjunction with the other parts of the system provides the customer with an affordable, durable, and well-tested LiDAR solution

## Measurement geometry

1 laser switching beam every 0.5s. Laser sampling at 150MHz. After FFT sampling of 36Hz – 18 measurements on each beam. First and last spectrum taken out due to possible beam switching delays. 16 remaining spectra averaged on each beam to produce 1Hz data.

Max wind speed ~30 m/s – design choice in the FFT to keep a good balance between range and resolution (0.11m/s).






## Wind Speed and Wind Direction Derivation

**Line Of Sight relation under homogeneous flow:**

$$Vlos_{1,2} = w\cos(\alpha) \pm u\sin(\alpha)$$

**Axial component :**

$$w = \frac{Vlos1 + Vlos2}{2\cos(\alpha)}$$

**Lateral component :**

$$u = \frac{Vlos2 - Vlos1}{2\sin(\alpha)}$$

**Incoming Wind Speed:**

$$V = \sqrt{u^2 + w^2}$$

**Relative Wind Direction ~ Misalignment:**

$$\varphi = \tan^{-1}\left(\frac{u}{w}\right)$$

# INTERFACE

The LiDAR is equipped with an RS-485 2-wires (ground as a reference) half-duplex communication interface for data transfer between the External System and the LiDAR Unit itself. A basic overview can be seen in Figure 1.

The sensor sends data telegrams with a baud rate of 19200 bps and communication settings:

- 8 data bits
- 1 stop bit
- No parity


*Figure 1: Principle block diagram*

Arbitration of the bus is made by timing, where the timeframe for incoming communication is expected right after the DATA packet, as seen in figure 2.

Every second the LiDAR transmits a telegram over the RS-485 bus. Each telegram is 37 bytes long. After the LiDAR is finished transmitting, it releases the bus and listens if the external controller starts to transmit data. A diagram of the bus timing can be seen in figure 3.

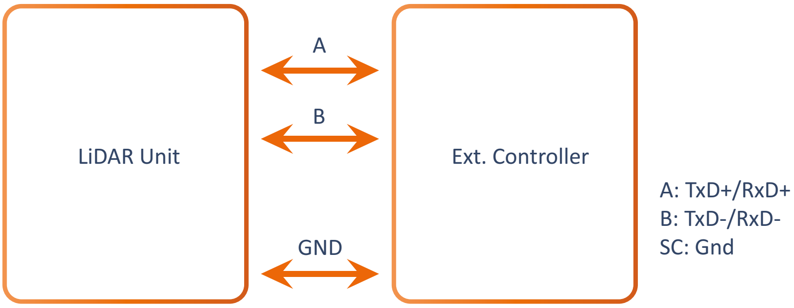



*Figure 2: BUS Principle block diagram*

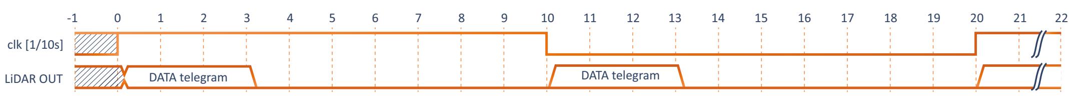


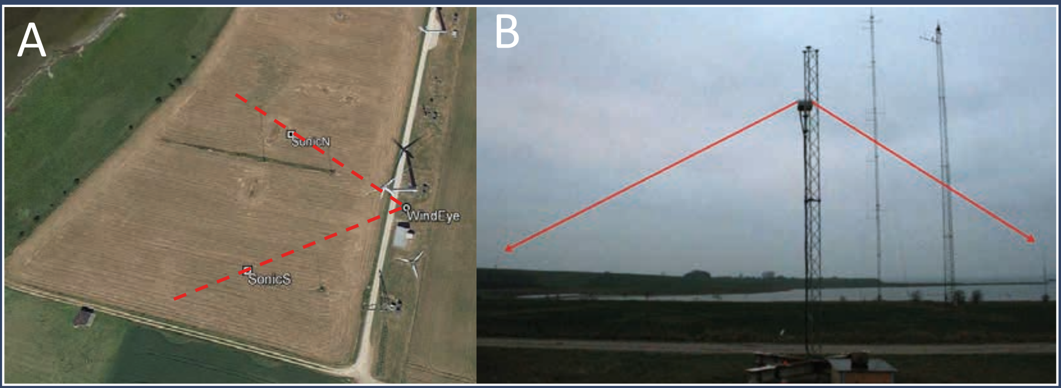

*Figure 3: RS485 bus timing*

# PRECISE MEASUREMENTS

The WindEYE™ has been tested against met. masts to validate the precision of the LiDAR's measurements. The below paragraph is from the test report from DTU Risø (Dellwik et al, Feb. 2015):

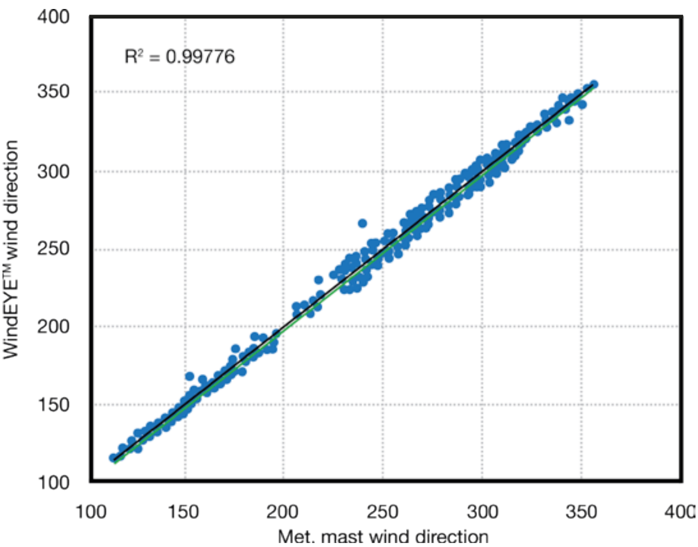
***"The functionality of a WindEYE™ LiDAR developed by Windar Photonics A/S for the wind energy market was tested in a two months long field experiment. The WindEYE™ sensor measures the wind speed along two beams to determine the wind direction of the incoming wind field.***

***The field experiment utilised two sonic anemometers, which were located in the two centers of the measurement volumes of the WindEYE™, as reference instruments. The wind vectors measured by the sonic anemometers were projected onto the line-of-sight directions of the WindEYE™ and the wind direction was calculated based on the WindEYE™ algorithm. It was found that the WindEYE™ measured the wind direction with a high accuracy during the whole campaign."***

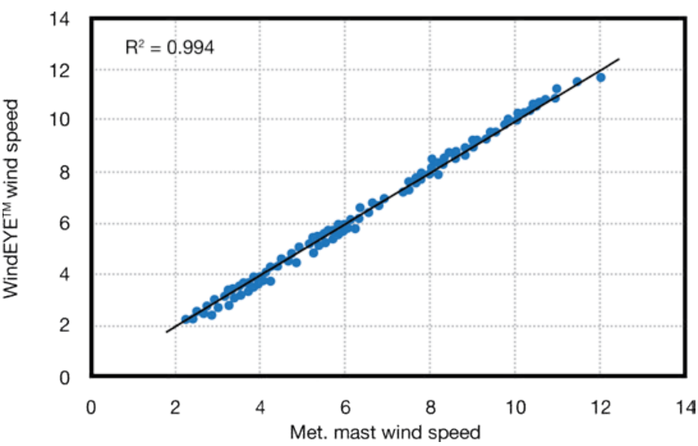



***Setup of the experiment: A. Positions of sonic anemometer masts and WindEYE™ at Risø campus, DTU, B. Photo of experiment.***

The following two diagrams display the correlation concerning wind speed and wind direction between the measurements of the Windar Photonics LiDAR and met. masts from the test at DTU Risø:



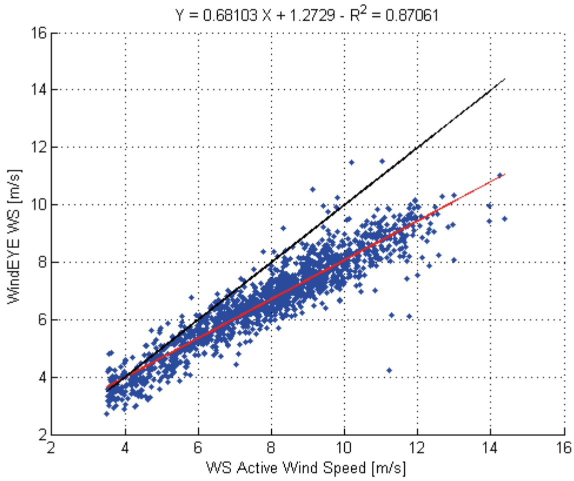

**Wind Direction**



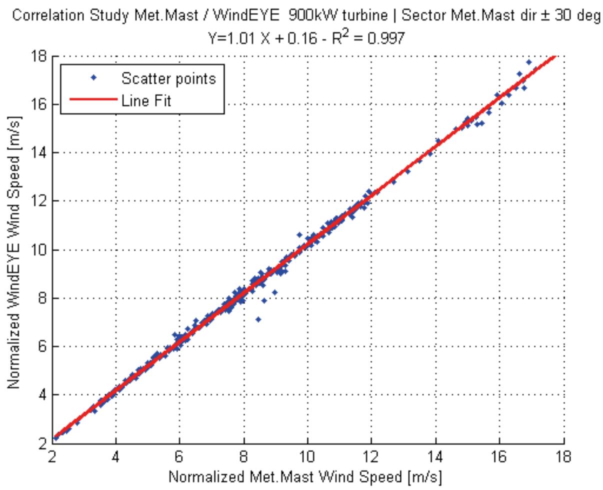

**Wind Speed**

The following two diagrams display the correlation between the measurements of the Windar Photonics LiDAR and conventional wind sensors, and between the Windar Photonics LiDAR and met. masts.

## WindEYE™ and Ultrasonic Wind Sensor




## WindEYE™ and Met. Mast



# CONTROL INTEGRATION

To be able to utilise the measurements and calculations from the LiDAR system, the wind turbine controller needs to be supplied with the information from the LiDAR system. This can be done in two different ways:

- By directly integrating either the WindEYE™ or the WindVISION™ LiDAR directly with the wind turbine controller as part of the design phase.
- Using the WindTIMIZER from Windar Photonics

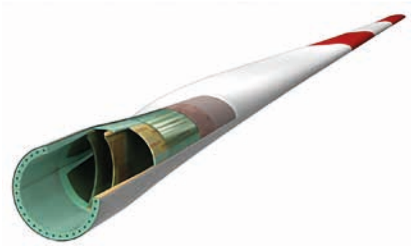
## Direct integration

Both the WindEYE™ and the WindVISION™ LiDAR can be integrated directly with the wind turbine control system as part of the design phase of the turbine.

## WindTIMIZER integration

The WindTIMIZER is a mediator solution that allows the Windar LiDAR to be integrated into the controller by proxy. In short, the WindTIMIZER converts the signal from the LiDAR to the protocol of the legacy anemometry, which can be send to the controller in place of the data from the legacy anemometry.

# LOADS

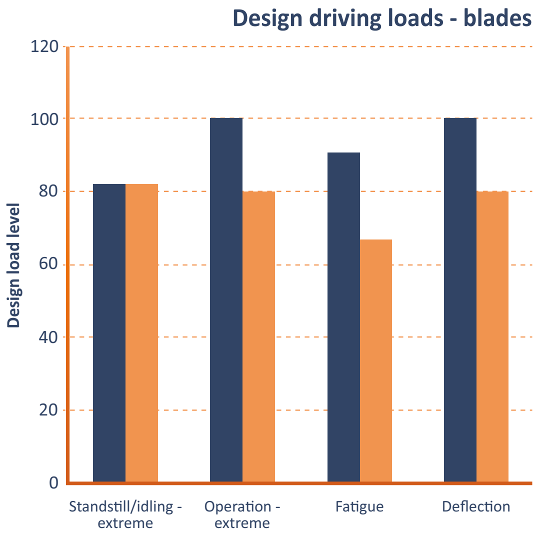


## Load detection and reduction

The Windar Photonics LiDARs are all capable of detecting various meteorological phenomenon that will affect the wind turbine by increasing loads on the mechanical parts. The measurements from the LiDAR can be utilised by the wind turbine owner to adjust the wind turbine to avoid unnecessary loads affecting and deteriorating the mechanical part of the turbine.

## Blades

The below graphs illustrates the gained decrease in loads with the LiDAR versus normal operation without the LiDAR in relation to the turbine blades. In general, *Fatigue* loads are reduced by up to 20%, while *Operation-extreme* and *Deflection* are likewise reduced.

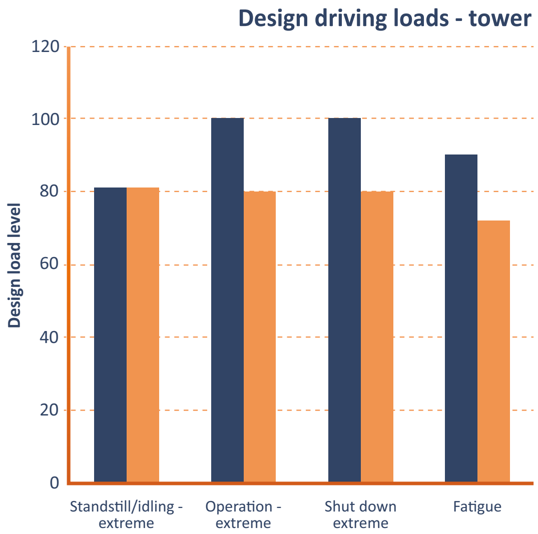



## CoE Reduction by 6-9%

By factoring in the maintenance costs related to the blades and rotor, it is possible to decrease the CoE by 6-9% with the Windar Photonics LiDARs’ pitch control.

## Tower

The load reducing effects of employing the Windar Photonics LiDARs are not exclusive to the blades, but will likewise have a momentous effect on the wind turbine tower. The below diagram displays the results of applying the LiDAR on a turbine versus a turbine without the LiDAR. Again, the application of the LiDAR results in lessened loads concerning general *Fatigue*. Likewise, during *Operation-extreme* and *Shut down extreme* the loads on the tower construction are significantly reduced with the LiDAR installed on the wind turbine.

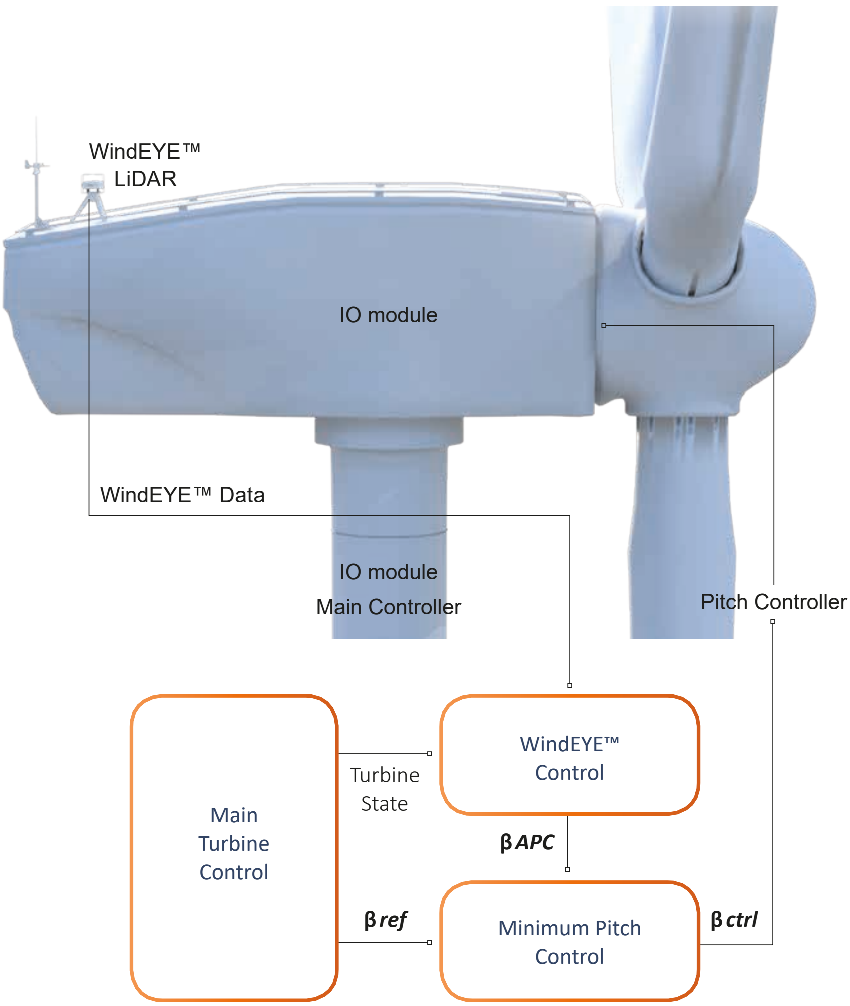


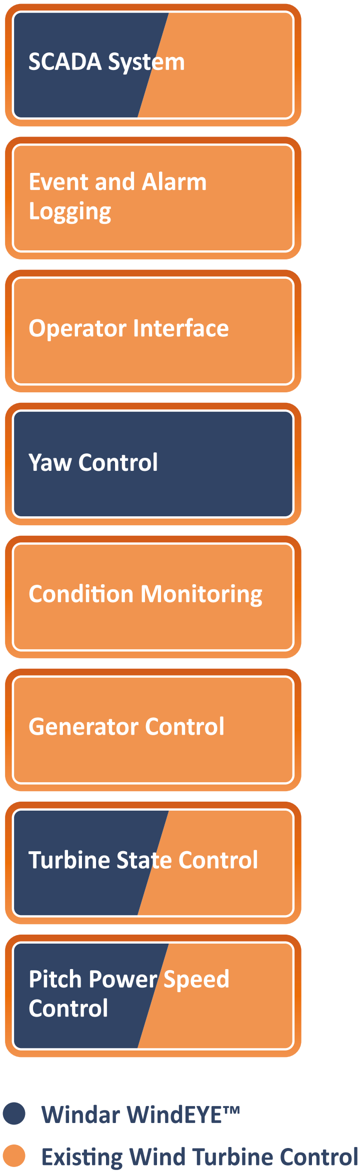

## Cost Savings of About 15-20%

The reduction in fatigue, tear, and wear on the turbine, as a result of the installed LiDAR, amounts to cost savings of about 15-20% on tower maintenance due to increased longevity.

# LOADS AND CONTROL

The optimisation benefits derived from the Windar Photonics LiDARS capacity to measure and detect various meteorological conditions are dependent upon the LiDAR's interaction with the wind turbine controller. The below diagram displays the WindEYE™ LiDAR's relation to the various control-related mechanisms of a wind turbine.






The WindEYE™ will have to influence different aspects of the wind turbine controller to optimise the yaw and pitch functions, including: Pitch Power Speed Control, Turbine State Control, Yaw Control, and the SCADA System.

The diagram displays the elements of the control system being affected by the WindEYE™; the blue colour designates that the particular aspect of the control system is influenced by the WindEYE™ - the amount of colouration denotes the degree of influence.

# SIMULATION IN DNV–GL'S BLADED SOFTWARE

Recently, the load reducing capabilitites of the Windar Photonics WindEYE™ LiDAR has been simulated in DNV-GL's *Bladed* software. The simulation was performed by the Austrian company AMSC, who reached the following conclusion[2] concerning the results:

## *"Simulation Results*

The results presented below are taken from simulations with a nacelle mounted LiDAR-system with a focal length of 70m. Although the controller set-up did not go through an optimisation process, a significant load-reduction potential for the tower-bottom is evident. Investigations show that the achievable load reduction depends on several factors (number of sampling points, sampling frequency etc.)

Ultimate loads: For production load cases reductions of up to 10% in the design relevant fore-aft direction could be found. Reductions for other components are found to be very small.

Fatigue loads: Reductions are achieved mainly at the tower-bottom and are in the range of 15%. Load-reductions for other components are not significant.

A retuning of the controllers and/or alternative control strategies that process additional information from the LiDAR-measurements such as wind-direction, wind shear etc. are expected to further improve the load-behaviour of the turbine.

For a better understanding of the control-behaviour, an example of an extreme load case dlc1.6 (EOG50) is shown in Figure 1. It can be seen that the blade pitch angle is moved towards feathering almost a second earlier compared to the baseline controller. This is a highly desirable behavior and reduces tower-bottom and blade loads significantly."

[2]: "LiDAR Assisted Control for Wind Turbines", [Dipl. Ing René Jilg, Dipl. Ing. Gottfried Slanitsch, Dipl. Ing. Albert Kušej, Dipl. Ing. Martin Göldner, Dipl. Ing. Michael Schwarz] AMSC Austria GmbH, TURBINE Magazine 04, pp.22-25, www.windarphotonics.com/turbine-magazine

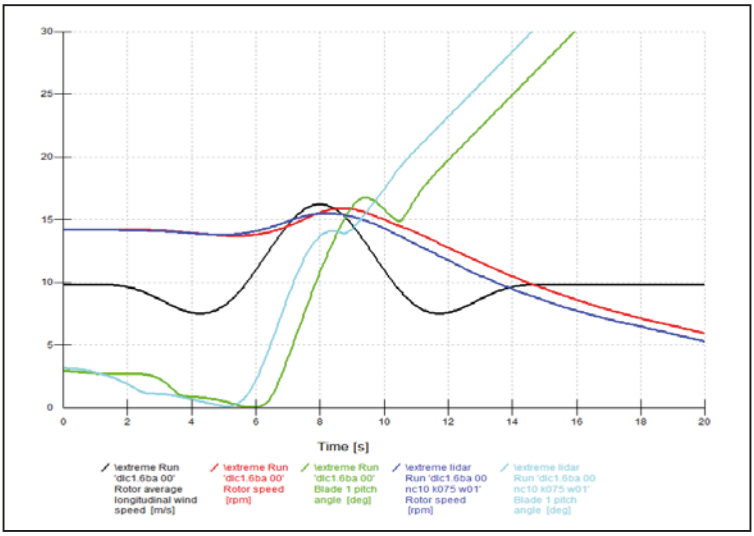



Figure 1 Extreme load case example

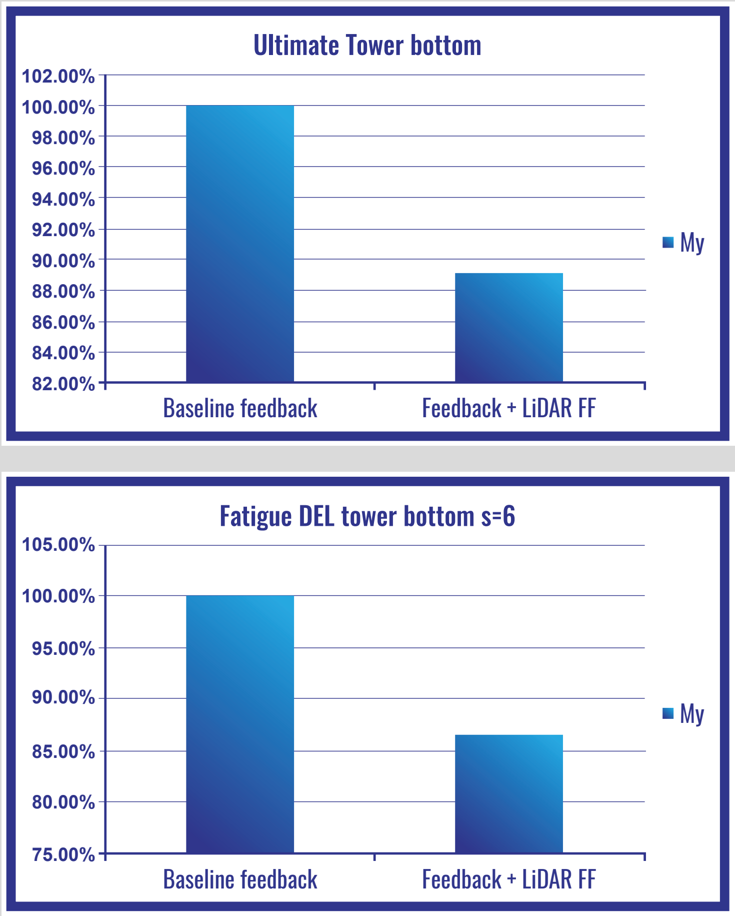



Figure 2 Loads for production load cases dlc1.1 only

# RETROFIT CASES

## Static vs. Dynamic yaw-misalignment correction

### The problems with the static yaw correction method

It is fairly well known that a significant part of the currently running wind turbines have yaw misalignment greater than 5 to 10 degrees, which results in a continual loss of AEP. Other manufacturers of LiDARs and measurement technology have tried to remedy this situation by offering a static realignment of the turbine to correct the yaw misalignment.

This method has been proved to work and will result in an average increase of AEP. However, there are three issues with this method:

**1.** Both the correction off-set and the projected hypothetical AEP increase are based on past measurement results, collected over a finite period of time. As it stands, there is currently no conclusive evidence as for how long the projected increase in AEP is valid from these measurement results, as the past measurement results do not necessarily correlate accurately with the actual and future meteorological conditions at the wind turbine site. As such, the correction and hence the hypothetical AEP increase could be valid for only a week, a month, or maybe only a few days, but nobody knows for sure.

**2.** The measurement period involved in the static correction method, as mentioned above, is based on a finite period of time, oftentimes only 1 to 3 weeks. It is by no means guaranteed that this is adequate and will include the necessary data for all wind bins, or even include enough data in general, to calculate a representative average for the correction of the turbine.

**3.** The average yaw correction degree calculated from the measurement results is applied to all the wind bins, even though the wind industry is well aware this is a methodological fallacy.

| Wind speed | Observed misalignment | | Misalignment after correction | |
|---|---|---|---|---|
| interval [m/s] | Mean | Absolute | Mean | Absolute |
| [ 4 - 5 ] | 3.67 | 7.78 | -1.08 | 4.09 |
| [ 5 - 6 ] | 4.85 | 6.33 | -0.16 | 3.40 |
| [ 6 - 7 ] | 4.04 | 6.04 | -0.58 | 3.13 |
| [ 7 - 8 ] | 4.07 | 6.10 | -0.50 | 3.29 |
| [ 8 - 9 ] | 4.58 | 6.09 | -0.40 | 3.11 |
| [ 9 - 10 ] | 6.67 | 5.49 | 1.07 | 2.86 |
| [ 10 - 11 ] | 7.56 | 5.47 | 1.37 | 2.53 |
| [ 11 - 12 ] | 8.35 | 5.46 | 1.74 | 2.58 |
| [ 12 - 13 ] | 6.85 | 4.81 | 0.92 | 2.42 |
| [ 13 - 14 ] | 5.57 | 3.80 | 0.01 | 2.00 |
| All | 4.96 | 6.15 | -0.17 | 3.23 |

*Measurement results for each wind bin*

## The practical implications of the static method

On a practical level, the static yaw correction method involves deploying the remote sensing equipment at the relevant wind turbine, then conducting the measurement campaign for a length of time, and lastly moving the remote sensing equipment to the next wind turbine in need of correction. This procedure is a practical necessity due to the costly nature of the remote sensing equipment. Additionally, further resources has to be spend on both the installation and deinstallation of the sensing equipment.

## Dynamic yaw misalignment correction

The problems inherent to static yaw misalignment correction can be alleviated by ensuring that the turbine is corrected according to actual and continuous measurements – in other words, dynamic correction. The Windar Photonics LiDAR optimisation solution, in contrast to the prevalent industry standards, is able to dynamically correct the yaw misalignment of the turbine by utilising the continuous measurements from the LiDAR sensor. By utilising a dynamic mode of yaw-alignment correction, the turbine is continuously corrected according to the actual meteorological conditions and not just the offset from a given measurement campaign.

## Static vs. Dynamic

| Static | | Dynamic |
|---|---|---|
| • Based on a calculated mean<br>• No integration w. turbine controller<br>• Requires constant calibration<br>• Ongoing costs for re-calibration<br>• More stoppage days for calibration<br>• Lesser degree of AEP increase | VS. | • Based on continuous measurements<br>• Integration w. turbine controller<br>• No manual calibration required<br>• Only requires normal maintenance<br>• Fewer stoppage days<br>• Greater degree of AEP increase |

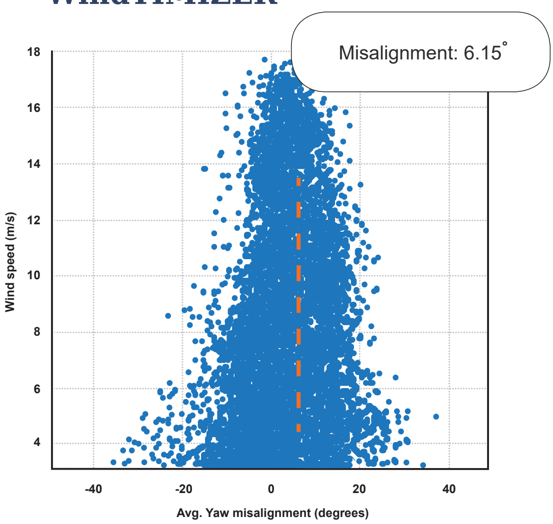

*WindEYE™ being aligned atop the nacelle*

## WindEYE™ and WindTIMIZER on a 2MW wind turbine

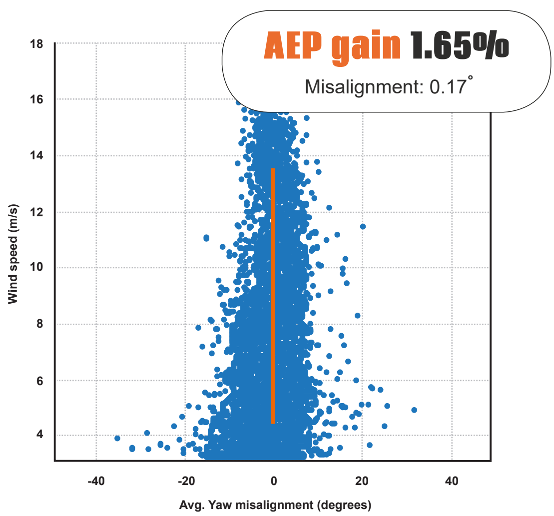
The following cases are based on a measurement campaign, where the WindEYE™ has been collecting data, which provides the initial degree of yaw misalignment. The plots containing the after results are a projection of the potential AEP gain, which can be achieved by utilising a control integrated WindEYE™.

In the *before plot* it is obvious that there is a rather large scatter, especially in the lower wind bins, whereas after the application of the WindEYE™ and the WindTIMIZER, the scatter for all the bins are narrowed down due to the proper alignment of the turbine. In this case, the wind turbine was misaligned by 6.15 degrees, which correlates with an AEP increase of 1.65%.

## Before the use of the WindTIMIZER

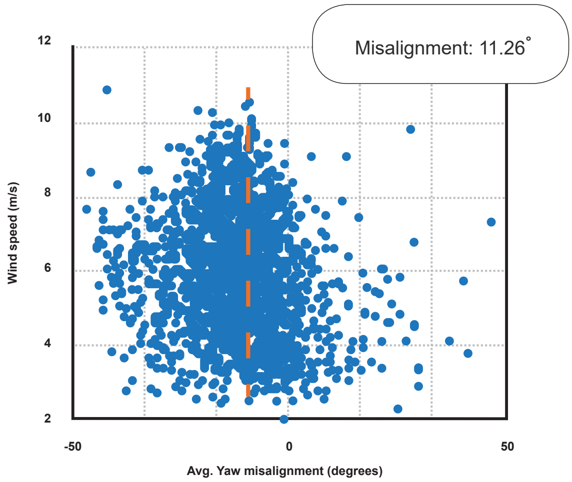



## After the use of the WindTIMIZER

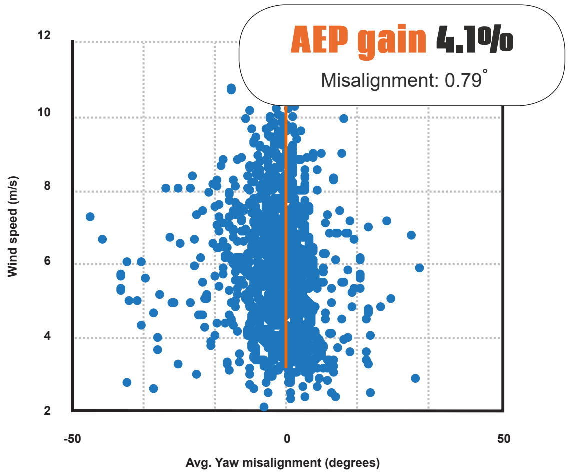



*The WindEYE™ and tripod mounted atop the nacelle*

## Before the use of the WindTIMIZER




## After the use of the WindTIMIZER



# PRODUCT TESTING

## Product testing:

**Windar's LiDARs have been subjected to a rigorous set of tests to ensure that the LiDAR can endure the harsh conditions on top the nacelle:**

- **EMC test**
- **Vibration Test**
- **Climate test**
- **Lightning strike test**

### Climate

IEC 60068-2-2:2007

IEC 60068-2-30 (2005)

IEC 60068-2-1:2007

IEC 60068-2-52

### Vibration

EN600068-2-6

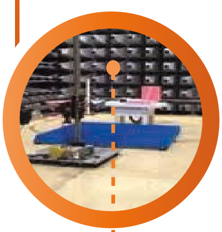
EN60068-2-64

Windar
Optical
head

DELTA

## EMC

EN61000-6-4:2007 A1: 2011
EN61000-6-2:2005
EN61000-4-2:2009
EN61000-4-4:2010
EN61000-4-3:2010
EN61000-4-5:2006
EN61000-4-6:2009
EN61000-4-8:2010
EN61000-4-9:1993 A1:2000
EN61000-4-10:1994 A1: 2001
EN61000-4-29:2001



Windar Optical head

## Lightning

IEC61400-24

Windar Optical head

# WINDAR PHOTONICS LIDAR FAQ

### *How are the windows on the system kept clean?*

The windows have been designed with dirt and dust resistance in mind, which allows normal rain to wash away any dirt or dust stuck on the lenses. During the ordinary service and maintenance of the turbine, the lenses can be manually cleaned with a soft cloth by the service technician.

### *How does dirt on the lenses affect the system?*

Theoretically, dirt on the lenses will affect the quality of the signal. However, we have never experienced an actual installation with windows that have been smudged to the extent of interfering with the signal - mostly due to the self-cleaning design that prevents any significant build-up of dirt or dust.

### *How does the weather conditions affect the LiDAR's performance?*

Most weather conditions does not influence the performance of the LiDAR as long as the LiDAR is able to measure the wind speed at the focus point. The only exception being heavy snowfall, which might affect the measurements. The general accuracy remains the same in most weather conditions, as it is an electronically derived value.

### *Won't the blades interfere with the LiDAR's measurements?*

The LiDAR detects the blades via 18 samplings per half second. If a sufficient share of the samplings shows the presence of a blade, the samplings from that half-second period will be flagged as a blade blockage and will subsequently be disregarded by the system.


### *How do you keep the LiDAR free of ice?*

The LiDAR is heated by an internal heating component that will keep a stable temperature of 20˚C inside the LiDAR at all times. The optical part of the LiDAR is insulated to ensure a positive surface temperature in all weather conditions. The windows are not heated or insulated, thus most of the heat is lost through the windows, which keeps them free of ice.

### *How much time is required for a LiDAR installation?*

The installation process takes about 4 to 5 hours for two technicians.

### *What kind of service and maintenance does the LiDAR require?*

The LiDAR only requires a minimum of maintenance and service, which can unproblematically coincide with the general service intervals of the wind turbine. On a practical level, the maintenance consists changing the laser every two years and wiping the windows on the LiDAR with a soft cloth, which takes less than 5 minutes.

Changing the laser is also a rather simple procedure, as changing the laser does not necessitate any calibration of the LiDAR.

## *How often do you need to calibrate the LiDAR?*

Nothing in the LiDAR can move physically or in any other way drift mechanically or electronically. Thus, no calibration is required to maintain the high accuracy of the LiDAR.

## *Is the LiDAR protected against lightning? Does it cover the parts both inside and outside the nacelle?*

The optics of the LiDAR is protected by a lightning cage, which is grounded to the turbine lightning cage.

## *Can we use the LiDAR for power curve measurements?*

Providing that the customer is willing to disregard the IEC-standard for power curve measurement: Yes – the LiDAR can in fact be used for power curve estimates that can be used as a day to day validation of the turbine performance.

## *Why do you not measure further than 80 meters in front of the turbine? Is a distance of 80 meters adequate to react on large turbines?*

In terms of anticipatory pitching strategies, measuring in the near field is optimal. The controller does not need much time to react in case of wind gusts. Furthermore, the angle of the beams can be specified during the design stage, easily allowing the LiDAR to reach the distance of 2/3rds of the rotor diameter of any turbine model currently in production, if required by the client.

# EPILOGUE

**It is our hope that we have managed to garner some interest in our LiDAR optimisation solutions, and hopefully we have managed to give a clear and comprehensive description of how LiDARs can contribute to reaping even more energy, and at the same time increase the longevity of wind turbines. As such, it is no longer necessary just imagining being able to predict the wind – now you are actually able to do so.**