LiDAR Application for WInd Energy Efficiency
Final report

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Publication date
2016

Document Version
Final published version

Citation (APA)
Boorsma, K., Wagenaar, J. W., Savenije, F. J., Boquet, M., Bierbooms, W., Giyanani, A., & Rutteman, R. (2016). *LiDAR Application for WInd Energy Efficiency: Final report*. (ECN-E--16-044 ed.) ECN.

LiDAR Application for WInd Energy Efficiency

Final report

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November 2016
ECN-E--16-044

Acknowledgement

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, voor het TKI Wind op Zee uitgevoerd door Rijksdienst voor Ondernemend Nederland.

The authors would like to thank TKI Wind op Zee for facilitating the project in their framework. Also the ECN part of the FP7 Windscanner.eu Prepatory Phase project is as a whole part of the LAWINE project. Therefore the authors acknowledge the European Committee. Within task B the defined measurement campaigns and subsequent data analyses have been performed in collaboration with DTU and the NORCOWE consortium represented in this case by the Christian Michelsen Research centre and the University of Bergen.

Abstract

ECN with its partners TU Delft, Avent LiDAR Technologies and XEMC Darwind executed the four-year TKI Wind op Zee project LAWINE (LiDAR Application for WInd Energy Efficiency). In this project the application of LiDAR technology has been developed and validated so that it can be used to improve the operation of offshore wind farms with the goal to further reduce the cost of offshore wind power plants. The planned deliverables in the project have been met within time and budget requirements. Gathering a project team that includes a variety of competences has resulted in a fruitful cooperation leading to the following interesting project results:

1. It has been verified that ground based LiDAR can be applied for wind resource assessments as well as power and loads assessment campaigns. This way wind turbine performance can be verified without the requirement of expensive masts.
2. Power performance assessments can be performed more accurately by using the wind profile measurements of the LiDAR.
3. Wake characterization by LiDAR measurements has been demonstrated, which will assist the optimization of lay-outs of offshore wind farms.
4. In the project it has been demonstrated that nacelle LiDARs are suitable to be used as basis in power performance assessments.
5. It has been demonstrated that LiDAR measurements in combination with advanced controllers have significant benefits for rotor speed regulation and reduction of fatigue loads.
6. It has been demonstrated that LiDARs can determine yaw misalignment accurately, which is an important aspect to implement the ECN wind farm controllers.
7. ECN developed the LiDAR calibration facility where industry can calibrate its LiDARs in a very effective manner. Such utility is crucial for the successful application of LiDARs in wind resource assessments and power performance verification.

These results have been disseminated with researchers and industry over various conferences and workshops.

Contents

Summary

An overview is given of the TKI Wind op Zee project LAWINE (LiDAR Application for WInd Energy Efficiency), which has researched the application of LiDAR technology to further reduce the cost of offshore wind power plants. Both coordinating aspects of the project as well as an overview of the technical achievements are described.

From a project coordination point of view, deliverables have been met whilst planning and budget requirements were generally complied with. Gathering a project team that includes a variety of competences has resulted in a fruitful and pleasant cooperation. Dissemination was achieved over various conferences and workshops.

From a technical point of view the large test campaign at the ECN test site, including ground based, nacelle based and scanning LiDARs was a great success. The test campaign has allowed to study and quantify numerous advantages of LiDAR technology. By doing so the project has contributed to further acceptance of LiDAR technology and a reduction of Cost of Energy. The main achievements per task are summarized below.

In Task A the capability (and added value above traditional anemometers) of using a ground based LiDAR for wind resource assessments as well as power and loads assessment campaigns has been verified. Generally speaking a very good correlation has been found with meteorological masts in terms of wind speed, direction and turbulence intensity. The multiple measurement heights of LiDARs allow characterization of atmospheric stability, which is an important parameter influencing wind turbine performance. In addition to that LiDAR technology was found to have added value for power performance and loads assessments campaigns, mainly due to availability of the extra measurement heights.

In Task B both a short and long range windscanner test were performed at the ECN test site. Analy-

sis of the results has indicated that using the measurement equipment the wake can successfully be characterized in terms of deficit, meandering and displacement as a function of inflow and atmospheric conditions.

In Task C, forward and/or backward looking LiDAR capabilities on the nacelle of wind turbines for power performance and wake analysis have been subject of research. The forwards looking campaign has demonstrated the suitability of nacelle LiDARs for application in power performance assessment. The backward looking LiDAR allowed investigation of wake recovery along the wake centerline, quantifying its dependence on operational and inflow conditions. Generally speaking a good correlation to simulations was found.

In Task D, models for the wind transfer between the LiDAR measurement and the rotor plane have been established, using both physical modelling and system identification approach. The resulting models estimate the incoming wind with sufficient accuracy to be applied for collective pitch control. A good correlation of LiDAR measurements and loads on the wind turbine rotor (blades) is obtained, which can be used to optimize the wind turbine controller for load reduction. To be able to analyze the impact of LiDAR based control on the wind turbine performance, the ECN Advanced Control Tool (ACT) has been extended with LiDAR sensors. It was found that LiDAR in principal does have significant benefits for rotor speed regulation and reduction of fatigue loads.

In Task E the application of LiDAR is researched to further optimize wind farm performance. For the active wake control concept (aiming at minimizing wake losses by actively ’steering’ the wake) it was found that LiDARs can play an important role because accurate determination of yaw misalignment is of prime importance for its successful implementation. Several possibilities are distinguished to optimize the performance of a wind farm with respect to its power production. A survey is made to determine the specifications (and corresponding LiDAR technology) needed for wake location determination as input to active wake control.

To accommodate the large measuring campaigns with LiDARs of nowadays, a complete data-acquisition package has been developed in Task F that can be used to acquire data from all kinds of devices. The package has successfully been tested during measurement campaigns at the ECN test site. The new data-acquisition package features a fully modular design, and is to be used with any kind of data-acquisition system. Furthermore it can be used with an unlimited amount of data-acquisition systems and measuring signals and is expandable without limitations due to the software architecture.

In Task G the WindScanner.eu Prepatory Phase project has been executed in the framework of FP7. The WindScanner.eu ERIC business plan is drafted, together with the statutes regarding the future ERIC [81]. A proof of concept regarding database set-up and access management was created by ECN, discussed with UPorto and presented to the consortium.

In Task H, a LiDAR calibration platform has been set-up at the ECN test site, both for ground based as well as nacelle based LiDARs. The facility was successfully demonstrated to be applicable for LiDAR calibration. A service has been developed to serve the industry.

1

Introduction

By the end of 2012, the LAWINE project [33] was initiated by ECN to develop technology and services using LiDAR systems in offshore wind power plants to significantly reduce the Cost of Energy:

- Better estimation of wind resource
- Efficient power performance assessments
- Optimizing turbine control
- Reduction of mechanical loads in wind farms

Development and analyses with LiDARs (of the ground based, nacelle based and scanning type) are subject of study. The project includes the Dutch contribution to the international windscanner.eu facility and ran until 30 September 2016.

This report gives an overview of the project, both from a technical as well coordinating point of view. Firstly a project description is given in Chapter 2, also containing details about the approach, budget, dissemination and other coordination aspects. Chapter 3 gives a summary of the technical achievements per task. Finally the impact of the project and of LiDAR technology are discussed in Chapter 4.

2

Project overview

A table containing main project information is given in Table 1

Table 1: Summary of main project information

Project title	LAWINE, Efficiency improvements by LiDAR assistance
Project number	TKIW01006
Project coordinator	ECN
Project period	1st October 2012 - 30th September 2016

The project partners are:

- ECN: Project coordinator, applied research
- Avent LiDAR Technologies: LiDAR manufacturer
- TU Delft: Fundamental research
- XEMC Darwind: Turbine manufacturer
- Windscanner partners: EU Collaboration with DTU Wind (Denmark), CENER (Spain), CRES (Greece), Fraunhofer (Germany), SINTEF (Norway), LNEG/INETI (Italy), Forwind (Germany), University of Porto (Portugal) and IPU (Denmark)

As such a strong consortium was built consisting of the whole technology chain from fundamental research to industrial application.

The project was divided into 8 work packages from A to H. These project tasks are defined to cover the numerous wind energy applications of LiDAR technology:

- Task A: Analysis and development of measurement technology and data processing technology to apply **ground based LiDARs** to wind resource assessments and turbulence assessments
- Task B: Analysis of capability of **wind scanning LiDAR** for wind field analysis (wakes, turbulent structures, atmospheric stability and wind shear)
- Task C: Analysis of forward and/or backwards looking LiDAR capabilities on the nacelle of wind turbines for **power performance and wake analysis**
- Task D: Development of **wind turbine control strategies** by making use of information of forward looking LiDAR capabilities on nacelle of wind turbine
- Task E: Wind farm optimization by **wind farm control strategies** supported by LiDAR wind field measurements
- Task F: Efficiency improvement in LiDAR measurement campaign
- Task G: Development of European research infrastructure for ESFRI
- Task H: LiDAR calibration

2.1 Objectives

The objective of this project is to reduce the levelized cost of wind energy by reducing the uncertainties of offshore wind farms. Here one can think of:

- Uncertainties in the wind resource by making available better measurement techniques of LiDAR measurements
- Uncertainties in the annual energy production by making available an accurate measurement technique based on nacelle based LiDARs
- Reduction of uncertainty in contracting and financing of wind farms by making available an efficient method for power performance assessments and yield of the wind farm
- Reduction of loads and optimisation of operation by implementation of nacelle based LiDAR measurements for turbine control
- Optimisation of wind farm operation by including wind field measurements in innovative wind farm control

- Making the pan-European windscanner.eu facility available for the Dutch Industry

In quantitative measures the objectives are:

- Uncertainties in wind resource assessment by using LiDARs will be in the same range of uncertainties using cup anemometers (that are still required by standardisation)
- A service is set-up that for cost-effective power performance assessments with nacelle-mounted lidars for offshore wind farms. The uncertainty needs to approach the uncertainty of standardised power performance assessments.
- For offshore wind turbines, the assessment of incoming wind field is essential for further reduction of costs by integrated LiDAR-assisted control technology. Especially the implementation of the LiDAR-wind field knowledge in wind farm control is a next step leading to cost reductions.
- The legal and organisational framework for the windscanner.eu pan-European facility is provided. This will lead to the realisation of a >40million euro mobile facility to measure wind fields in large wind farms.
- A calibration test range is set up at the ECN test site so LiDARs can be calibrated for use in wind energy applications.

2.2 Approach

The project has been organised around extensive measurement programs situated at the ECN Wind turbine Test site Wieringermeer (EWTW). An overview of the test site is given in Figure 1. A summary of the performed installations is given below:

- LiDAR measurements at EWTW in combination with 2.5MW research wind turbines and meteo masts
- LiDAR measurements at EWTW of LiDAR on nacelle of multi-MW wind turbine
- Wind scanner in scale wind farm
- Wind scanner in EWTW research wind farm (2.5MW wind turbines)
- Prototype LiDAR placed on nacelle of XEMC Darwind turbine that captures wind shear
- Development of LiDAR calibration measurement range at EWTW

For more details about the campaign, the measurement plans [52, 6], instrumentation report [40] and completion report [5] can be consulted.

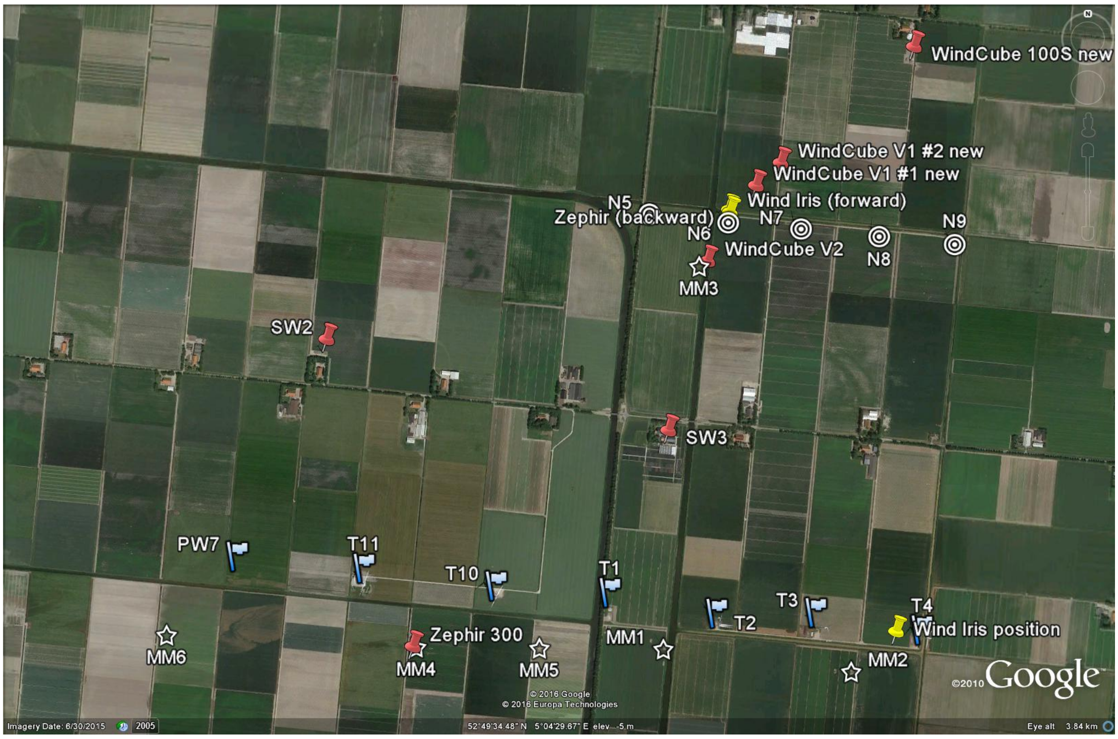


Figure 1: Layout of the EWTW test site with the research turbines (N5 - 9), the prototype turbines, the meteorological masts, the measurement office and the LAWINE LiDAR locations. The top side of the figure resembles north

ECN was coordinator, provided the ECN test site, performed the experiments and analysed data. TU Delft is provided a PhD student for the fundamental research. Avent LiDAR Technologies provided the nacelle-mounted LiDARs and XEMC Darwind provided a prototype wind turbine as test platform. The project has also contributed to setting up the windscanner.eu mobile test facility that is developed in Europe.

2.3 Coordination

Apart from the frequent email-traffic, half year meetings were organized to facilitate cooperation between the partners [55, 54, 57, 56, 58, 59]. Here the meeting host has varied between the project partners. Generally speaking these meetings provided a platform to give feedback and enhance the research. But also making arrangements regarding the operational characteristics that accompany setting up a large test campaign has benefitted from the regular meetings. A project teamsite was established to facilitate the exchange of data and reports. Apart from organizing the meetings and facilitating contact, the coordinator has had its hand in steering the project results towards the defined deliverables, within the defined temporal and financial boundaries. A yearly progress report has been submitted to the sponsor. Gathering a project team that includes a variety of competences has resulted in a fruitful and pleasant cooperation. Having a project partner abroad appeared to result in language issues as much of the sponsor documentation was only available in Dutch and translation efforts had to be undertaken by the project coordinator. An overview of the financial running of the project is given in the section below.

2.3.1 Finance

Generally speaking all partners have performed their tasks within the allocated subsidy. However several modifications were requested and mostly granted, mainly to the ECN part, because they all remained within the maximum of 25% of the original budget and improved the project result. A summary is given below.

- Cost shifts
  Several costs shifts (for the same total budget) were effectuated by ECN throughout the project. It appeared that several material and other non-hour related costs were better spent as labour cost. The differentiation of costs between the several tasks also turned out differently compared to the original planning.
- EU Windscanner spending
  In task G more budget was spend than originally planned, although the total project budget remained the same. In short, ECN decided to define more activities in this task, because in general ECN believes in the WindScanner initiative that goes beyond the scope of the WindScanner.eu PP project. The additional activities are summarized as: WindScanner exploration outside wind energy, WindScanner.eu database proof of concept and definition of pilot project.
- PhD student
  TU Delft found a suitable PhD candidate after the project had already kicked-off. As a consequence the PhD thesis will be finished after the project has ended, which is accepted by RVO. To allow justification of part of the supervision hours of the project partners, it was requested to postpone the ending of the project and particularly Task D. Unfortunately the request was negated, due to the maximum project duration demand of four years and the necessity for timely availability of project results.

2.4 Dissemination and Collaboration

Apart from the numerous technical reports written, several conferences and events have been visited to share project results and obtain feedback from the community. An overview of selected dissemination events and publications is given below.

- Press releases [1, 2]
- IEA Task 32 meetings
  - Kick-off meeting: Roskilde, May 2011
  - Progress meeting: Oldenburg, November 2012

  - Progress meeting: Stuttgart, March 2014
  - Progress meeting: Glasgow, November 2014
  - Workshop on “Recommended practices for the use of floating LiDAR systems”: London, February 2016
  - Workshop on “LiDAR measurements for wake assessment and comparison with wake models (joint workshop with IEA Wind task 31 Wakebench)”: Munich, October 2016
  - (Planned) Workshop on “Power Performance: Round Robin for FDIS IEC 61400-12-1 Ed. 2 Calculation of Uncertainty for LiDAR application”: Glasgow, December 2016

- TKI WoZ Matchmaking day 2013: LAWINE LiDAR Application for Wind farm Efficiency [68]
- EWEA Offshore 2013: Enhancing LiDAR application for boosting Wind Farm Efficiency [77]
- Windkracht 14: Large LiDAR experiment at ECN wind turbine test site, Improving the performance of wind farms [69]
- EWEA 2014: Turbine performance validation; the application of nacelle LiDAR [78]
- EWEA Offshore 2015: Using backward nacelle LiDAR in wake characterization for wind farm optimization [53]
- DEWEK 2015: Effects of rotor induction on the propagation of disturbances towards wind turbines [8]
- Wind days 2016: Shining LiDAR light on wind farm efficiency; On the reduction of Cost of Energy using LiDAR technology [60]
- Aerospace Engineering (TU Delft) PhD Poster Day 2014 [12]
- 14, 16th EMS Annual Meeting & 10, 11th European Conference on Applied Climatology (ECAC) [21, 22]
- EAWE (European Academy of Wind Energy) 10th and 11th PhD Seminar on Wind Energy in Europe [17, 19]
- Delft Energy Initiative (DEI, TU Delft) PhD poster event 2015 [18]
- 6th Conference on “The Science of Making Torque from Wind” (TORQUE2016) [23]
- Publication in ’Technisch Weekblad’ [3]
- The LAWINE project resulted in numerous internal publications at the involved project partners (e.g. [13, 14, 38, 64, 11, 45, 37, 10, 73])

2.4.1 Collaborations

Outside the collaboration between project partners, several other institutes have been involved in the project.

- Part of Task B and Task G has been executed in close collaboration with the WindScanner.eu (`http://www.windscanner.eu`) partners, being CENER, CRES, DTU, ECN, ForWind Oldenburg, Fraunhofer IWES, LNEG, Sintef and University of Porto.

- Part of Task B is executed in close collaboration with the NORCOWE consortium (`www.norcowe.no`), represented in this situation by Christian Michelsen Research (CMR) centre and University of Bergen (UiB). The work, technically described in section 3.2, has led to several contributions to NORCOWE conferences (2013, 2014 and 2015) and other international conferences [44, 76, 53].

- ECN participated in the International Energy Agency (IEA) Wind Annex 32: LiDAR and attended the meetings listed above.

  More particularly and in phase 1 of the task ECN participated in and contributed to subtask 1.5 'Calibration methods for Floating LiDAR ', subtask 3.1 'Exchange of experience in power performance testing using a ground based LiDAR according to IEC 61400-12-1 ed 2 Annex L' and subtask 3.3 'Nacelle based power performance testing' and provided input for subtask 2.3 'Using LiDAR for turbulence measurements' and subtask 2.4 'Using LiDAR for wind resource assessment'.

  An overview report is provided in [63]. Particular outcome with respect to subtask 1.5 is the "State-of-the-Art Report: Recommended Practice for Floating LiDAR Systems" [67], followed up in the framework of the Carbon Trust Offshore Wind Accelerator "Offshore Wind Accelerator Recommended Practices for Floating LiDAR Systems" [66], and with respect to subtask 3.1 the 'Rotor equivalent wind speed for power curve measurement – comparative exercise for IEA Wind Annex 32' paper [72] for the Science of Making Torque from Wind conference 2014.

3

Technical Achievements

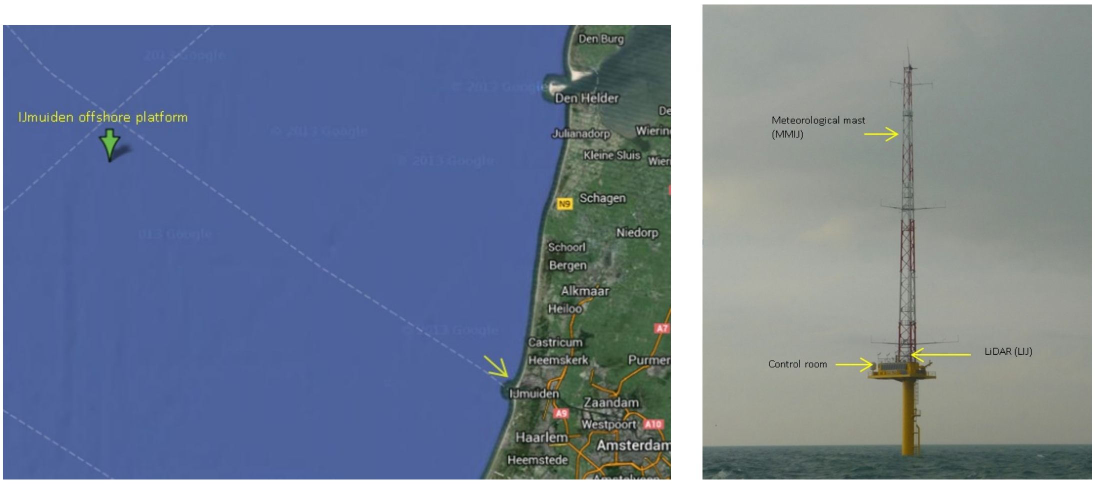
3.1 Task A: Ground based LiDAR

The capability (and added value above traditional anemometers) of using a ground based LiDAR for wind resource assessments as well as power and loads assessment campaigns has been verified. Generally speaking a very good correlation has been found with meteorological masts in terms of wind speed, direction and turbulence intensity. The multiple measurement heights of LiDARs allow characterization of atmospheric stability, which is an important parameter influencing wind turbine performance. In addition to that LiDAR technology was found to have added value for power performance and loads assessments campaigns, mainly due to availability of the extra measurement heights.

3.1.1 Wind resource assessment

In addition to the WindCube positioned next to meteorological mast 3 at the ECN Wind turbine Test site Wieringermeer (EWTW) (see also Figure 1), the offshore offshore placed meteorological platform Ijmuiden [80] (including a Zephir LiDAR), depicted in Figure 2, was used to study wind resource assessment using LiDAR technology.

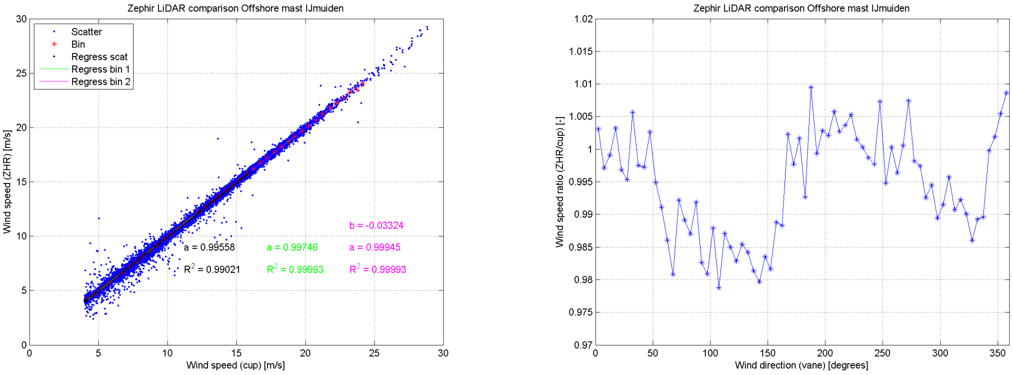
For the offshore platform, the bin-averaged regression indicates an excellent agreement between cup and LiDAR wind speed measurements, its relative deviation is in the order of 1% and its uncertainty varies from 1.2% to 2.2%. The regression lines are depicted in Figure 3(a). Plotting the unfiltered ratio of the two wind speed measuring devices as a function of wind direction (Figure 3(b)) reveals the influence of the mast including suspension booms on the cup measurements, which is a distortion that the LiDAR measurements donot suffer from. The system availability of the LiDAR at was larger than 95% of which a very small percentage is not useful due to atmospheric effects (e.g. insufficient backscatter) depending on measurement height. Many more aspects including wind direction (wind rose), turbulence inten-



(a) Location in the North Sea

(b) Platform including meteorological mast and LiDAR

Figure 2: Offshore placed meteorological platform IJmuiden [45]



(a) Wind speed comparison

(b) Wind speed ratio as function of wind direction

Figure 3: Wind resource assessment at the IJmuiden platform

sity, wind shear profile, seasonal variations and histograms were assessed, generally to a satisfactory agreement. Details can be found in the dedicated report [45]. For the turbulence intensity, it was found that for low wind speeds differences can be observed between LiDAR and cup measurements, probably caused by the inertia of the cup anemometer itself.

This offset was confirmed also at EWTW, where a dedicated study was performed to compare turbulence intensity between cup, sonic and LiDAR measurements [37]. In general, the results with the LiDARs are in better agreement with the sonic anemometers than with the cups. Especially at lower wind speeds (< 4 m/s), the turbulence intensities measured with cups result in approximately 2-4% lower values compared to sonic anemometers, and 2-6% lower values compared to LiDARs. At higher wind speeds (>5 m/s), the LiDARs measure slightly lower turbulence intensities (<0.5%) compared to sonic anemometers, and higher turbulence intensities (<1%) compared to cups. In general, turbulence intensities measured with the ground based LiDAR are in between the results measured with cups and sonics, which demonstrates that the accuracy of the LiDAR technique for turbulence measurements is satisfactory. Moreover, the reproducibility of the LiDAR technique turned out to be very good.

Similar to the IJmuiden result, the wind speed comparison between LiDAR and traditional anemometers at EWTW also proved an excellent agreement [42]. The advantage of the test field over the IJmuiden platform data is the availability of the research turbines, allowing a quantification of the turbine power output as well. The energy production of a 2.5 MW research wind turbine at EWTW is calculated using a meteorological mast and a ground-based LiDAR (assuming the provided power curve data) and then, it is compared to the actual power production of this turbine [11]. Deficits in the expected and actual energy yield using hub height wind speed are 2.9% when using a meteorological mast and 0.7% using the ground based LiDAR. In this study, the applicability of both devices to perform energy yield estimations at EWTW was found to be similar. Furthermore, there was no evidence to suggest that there would be added value in using the rotor equivalent wind speed for calculating energy yield at the current site. However, further work in this area and a larger data set would assist in verifying this claim.

Atmosperic stability

Another added value of LiDAR measurements lies in the fact that measuring at multiple heights over a large range allows monitoring atmospheric stability. Observation data obtained from meteomast IJmuiden has been analyzed to assess if Monin-Obukhov (MO) similarity theory can be used to describe the far offshore marine atmosphere [62]. It is concluded that MO-theory can be applied to describe wind shear and turbulence, unless the atmosphere has a strong stable stratification. Both wind shear and turbulence depend strongly on stability, expressed as the non-dimensional stability parameter ζ=z/L (with z the height above the surface and L the Obukhov length). In general, in (late) autumn and winter the sea surface temperature will be above the air temperature, so the atmosphere will be unstable. In (late) spring and summer the opposite will be the case, so stable conditions.

For conditions where the boundary layer is sufficiently deep, the Businger-Dyer functions can be used to describe wind shear. For stable conditions (positive ζ values) the scatter is significant, and the formulation by Holtslag and de Bruin seems to perform better compared to the Businger-Dyer relations, see Figure 4. With respect to turbulence, it is found that the normalised second-order moments are proportional to $(-\zeta)^{1/3}$ for unstable conditions, and proportional to $\zeta^{-1/2}$ for stable conditions. For neutral conditions the non-dimensional second-order moments are small compared to results found in literature. The stability dependence for stable conditions is typically not found in literature, but clearly present in the considered data. Combined, it is clear that for far offshore sites atmospheric stability is a crucial parameter, and one can approximate wind shear and turbulence with relative simple relations as

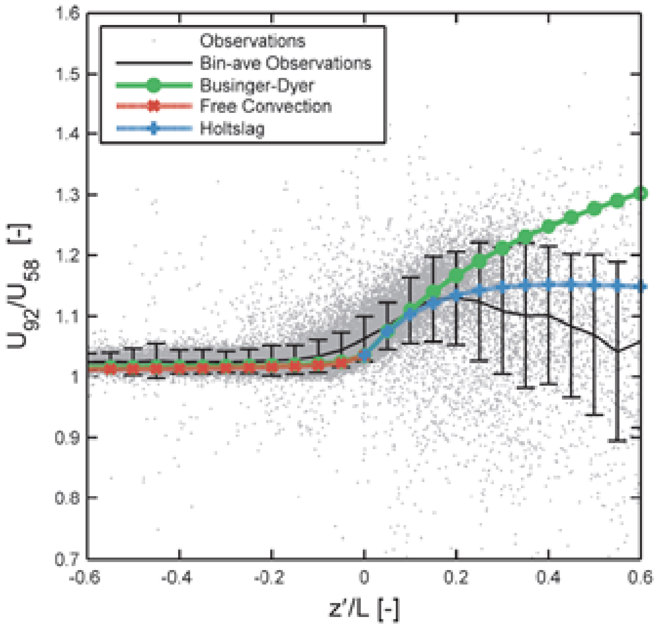


Figure 4: Wind shear ratio as a function of atmospheric stability (z'/L) according to observations and specific shear models (see legend). The solid thin line is the bin-averaged observations with error bars indicating one standard deviation within the bin [62].

a function of stability. From the measured data it is observed that high wind shear never occurs simultaneous with a high turbulence level. This is one of the main reasons that the IEC standard is conservative. Low Level Jets (LLJ) as well as turbulence spectra have been investigated as well.

3.1.2 Power performance and loads campaigns using LiDAR

At the EWTW a LiDAR was used to assess the power performance of the research turbine N6. Here, the methodology adopted is the one of the so-called Rotor Equivalent Wind Speed (REWS) in which multiple measurements across the rotor plane are considered. This methodology, specified in the new, draft standards for power performance FDIS IEC 61400-12-1 [4], is adopted because the hub height wind speed is considered not to be representative anymore for the inflow wind field of the rotor, which increase even more. This study has been used in a comparative exercise organized within the International Energy Agency (IEA) Wind Annex 32 context in order to test the REWS method under various conditions of wind shear and measurement techniques. Eight organizations, among which ECN, from five countries participated in the exercise. Each participant has derived both the power curve based on the wind speed at hub height and the power curve based on the REWS. This yielded results for different wind turbines, located in diverse types of terrain and where the wind speed profile was measured with different instruments (mast or various LiDARs). The participants carried out two preliminary steps in order to reach consensus on how to implement the REWS method. First, they all derived the REWS for one 10 minute wind speed profile. Secondly, they all derived the power curves for one dataset. The main point requiring consensus was the definition of the segment area used as weighting for the wind speeds measured at the various heights in the calculation of the REWS. This comparative exercise showed that the REWS method results in a significant difference compared to the standard method using the wind speed at hub height in conditions with large shear and low turbulence intensity [72].

As the LiDAR measures wind speeds at multiple heights, taking into account wind shear could result in a better correlation between measured loads and the wind. An investigation has been made to study the effect of the measured wind resource characteristics by means of LiDAR on the turbine behavior in terms of mechanical loads [64]. In particular the effect of vertical shear on turbine loads is investigated. Hereto measurement data from the campaign at EWTW (Figure 1) including an instrumented turbine, a met mast and a ground based LiDAR were analysed. Distribution of shear in the data was studied and the shear exponent α in the dataset was found to be inversely correlated to turbulence intensity. This correlation precluded drawing firm conclusion on the effect of wind shear on blade out-of-plane fatigue bending moment, because turbulence intensity is a dominant factor determining this moment. Filtering the dataset for low turbulence intensity does reveal the expected increase of this moment with increasing shear. Further observations are made on shear-dependency for blade, main shaft and tower loads. Ground-based LiDAR measurements are concluded to provide a suitable method for refined determination of turbine loads.

3.2 Task B: WindScanner experiments

Within this task both a short and long range windscanner test were performed at the ECN test site. Analysis of the results has indicated that using the measurement equipment the wake can successfully be characterized in terms of deficit, meandering and displacement as a function of inflow and atmospheric conditions.

3.2.1 Background

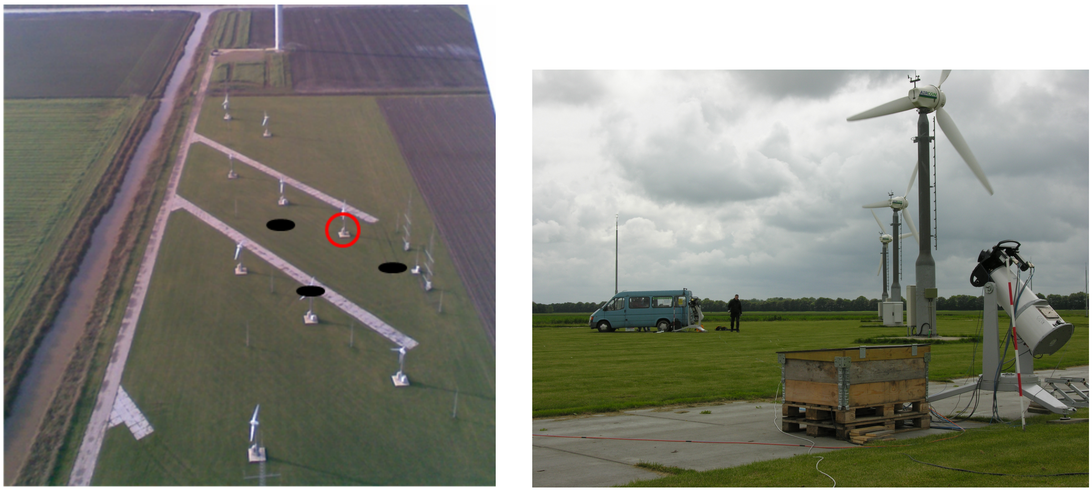
One of the goals of the LAWINE project is to make more accurate wind resource assessments using LiDAR technology. In task B this goal is specified in terms of the technological development of the WindScanner facility, while the development of the WindScanner facility in terms of organization,legal aspects etc. is defined in task G (section 3.7). One of the technological development components is to perform WindScanner tests in the field. Therefore, such tests are defined in this task B in two ways: A short range windscanner test was performed in ECN's scaled wind farm and a long range scanning LiDAR test was performed in the ECN Wind turbine Test site Wieringermeer (EWTW). The measurements are described in the measurement plan [6], together with the instrumentation report [40].

3.2.2 Short range windscanner in ECN's Scaled Wind Farm

Within this research infrastructure short range windscanners are scanners developed at DTU based on Zephir technology with a typical range from 10m - 150m. The 3 scanners operate together where the 3 separate beams are focused on one point in space and time to reveal the 3D nature of the wind. The development of these scanners still is in an early phase and in addition they are at this point considered as research tools. The ranges of the short range windscanners match very well with the typical distances in ECN's scaled wind farm. This scaled wind farm has a huge and extensive measurement infrastructure with many meteorological masts measuring the wind at multiple heights. Development of the short range windscanners are enhanced with tests in the scaled wind farm.

The aim of the campaign is to (1) capture the single wake of the red circled turbine in figure 5(a) anticipating on winds ranging from North to West. In addition it is aimed to (2) validate the short range windscanner wind measurements with the cup, sonic and vane measurements from the 5 meteorological masts rigth in figure 5(a). Last but not least it is aimed to (3) capture farm wakes, i.e. multiple wakes across the farm. An overview is provided in figure 5 and the details are elaborated in the measurement plan and instrumentation report [6, 40]. A measurement campaign was organized together with DTU and with a student from UPorto from the 26th of June 2014 until the 2nd of July 2013. In this campaign particularly the goals (1) and (2) have been addressed. Unfortunately, after finishing the measurement campaign and during post-processing DTU discovered malfunctioning of the windscanner system. Therefore, proper data was stated not to be possible and therefore, the goals (1), (2) and (3) could not be achieved.

Still, the aim of task B is to develop the WindScanner facility from technological perspective. In that respect the campaign has provided valuable feedback on logistics, planning and setting up a WindScanner



(a) Scaled wind farm layout with turbine under test (red circle) and indicated scanner positions (black dots)

(b) Photograph of scaled wind farm test

Figure 5: Scaled wind farm test

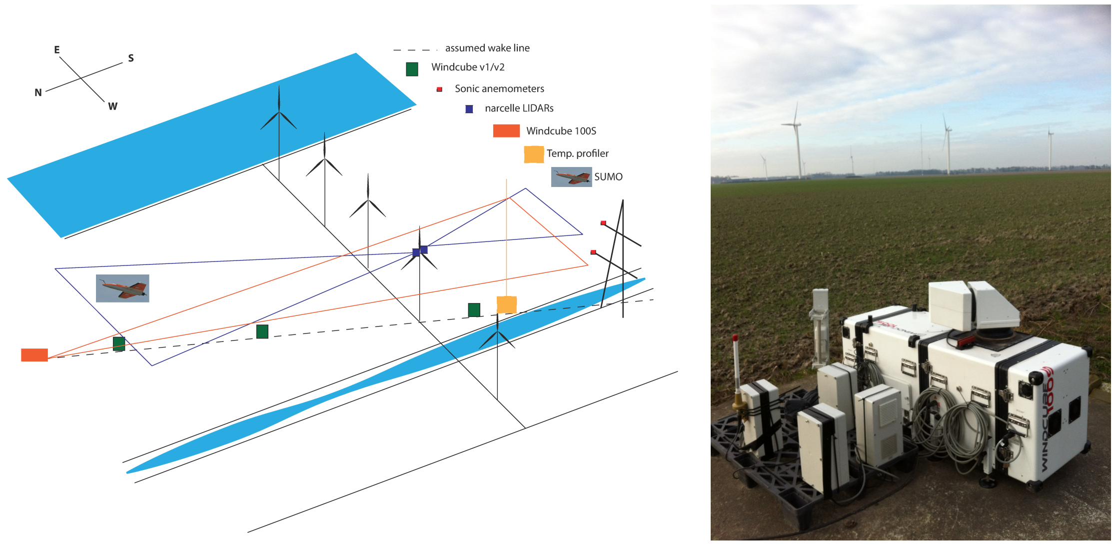
type of campaign. Although the specific goals have not been achieved the lessons learned definitely help to further develop the facility.

3.2.3 Long range scanning LiDAR at ECN test site EWTW

Next to short range windscanners also long range windscanners exist with typical ranges from several hundreds of meters to several kilometers. In order to technically further develop the WindScanner facility in this respect a measurement campaign was organized at the ECN test site EWTW together with the Norwegian research consortium NORCOWE, represented here by the Christian Michelsen Research centre (CMR) and the University of Bergen (UiB).

The aim of the project is to capture the wake of one of the ECN research turbines, second in the row from West and indicated as N6. In order to do so a large number of LiDARs are used to fully capture inflow and wake conditions. Key aspect is the WindCube 100S scanning LiDAR at about 1km North-East of the turbine under consideration, scanning the wake of the turbine for anticipated winds from South-West. In addition, 1 WindCube V1 ground based LiDAR is positioned upfront the turbine, next to meteorological mast 3 and 2 WindCube V1 ground based LiDARs are positioned downstream the turbine at ranges 2D-4D. A Zephir prototype nacelle LiDAR is placed in backward looking mode on the research turbine for wake measurements. All these LiDARs are brought in by NORCOWE. Already present at the site are the WindCube V2 ground based LiDAR next to meteorological mast 3 (see also section 3.1) and the forward looking Wind Iris nacelle LiDAR (see also section 3.3). An overview is provided in figure 6 and the details are elaborated in the measurement plan [6].

The analysis of the data measured by the scanning LiDAR LEOSPHERE WindCube 100S in the measure-



(a) Layout of the measurement campaign. The orange block indicates the position of the WindCube 100S scanning LiDAR

(b) Photograph of the WindCube 100S scanning LiDAR

Figure 6: ECN test site campaign with NORCOWE

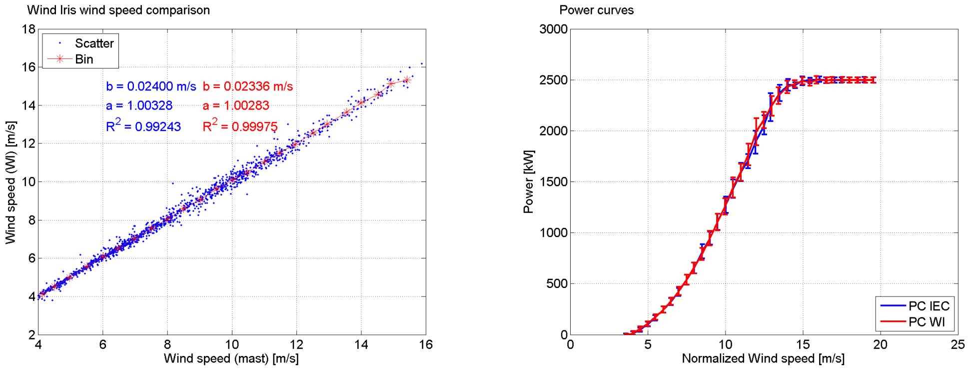
ment campaign have been executed in two student projects [24, 70]. In the first project, the properties of the LiDAR measurement are studied, and the general characteristics of the data are analyzed. Subsequently, several methods of wind speed reconstruction are developed and validated with the reference measurement, i.e. the WindCube V1 measurements. It is meant to reconstruct the horizontal wind velocity vector form the measured data (radial wind speed, azimuth angle, elevation angle etc.) of the scanning LiDAR WindCube 100S. From the analysis it is found that the tested methods do not yield very satisfying results. Therefore, a new method is recommended and described for the future study. In the end, a method of the wake visualization is developed and tested. The achievement and limits of this method is discussed and some recommendations are given in the end for the future study [24].

In the second student project [70] the framework of Aitken et al. [65] was adopted to extract wind turbine wake characteristics from LiDAR measurements recorded in the wake of an utility-scale wind turbine during a seven-month field campaign at EWTW. The velocity deficit in the wake, along with spatial characteristics like the span-wise and vertical extent of the wake and the transverse displacement of the wake with respect to the mean wind direction were studied in different atmospheric conditions.

Among others, the velocity deficit in the wake was found to first increase behind the wind turbine, up to the point where turbulent mixing between the wake and the free-stream flow becomes dominant over pressure effects. In case of convective conditions, the maximum velocity deficit was typically attained around 1D to 1.5D downstream of the wind turbine. In contrast, stable conditions showed a larger maximum deficit at 2D behind the rotor. Further, the magnitude of the maximum velocity deficit was strongly dependent on the free-stream wind speed, decreasing from around 70% for wind speeds below 6m/s to only about 30% at wind speeds over 12m/s. At these high wind speeds the blade pitch is adjusted, resulting in a smaller fraction of the kinetic energy being extracted from the wind.

After about two diameters downstream of the turbine, turbulent mixing between the wake and the free-stream flow leads to a gradual recovery of the wind speed in the wake. The velocity deficit was found to be generally higher in stable conditions as compared to convective conditions up to at least 5D behind the wind turbine. Likewise, a higher velocity deficit was also observed in case of a low ambient TI. However, due to the suboptimal site geometry (discussed in detail below) and the inherent difficulty of distinguishing low velocity deficits from ambient turbulence, no conclusions can be drawn on the rate of wake recovery in different conditions.

In addition it was found that the wake expands more for high ambient turbulence intensity conditions, because of larger turbulent mixing at the boundaries of the wake. Also, displacement of the wake center was observed for stable atmospheric conditions. Because the LiDAR is operated from the ground and the beam has a certain tilt angle, the wake measurement captures shear as well. Therefore, the effect of wind veer, particularly present during stable conditions might explain the observed wake center displacement. For details the reader is referred to the resulting report [70].



(a) Wind Iris wind speed against met mast wind speed for 10 minute averages (blue) and binned averages (red)

(b) Power against the normalized wind speed as measured with the mast (blue) and LiDAR (red). Total uncertainties are indicated

Figure 7: Results of the Wind Iris forward looking campaign [78].

3.3 Task C: Nacelle based LiDAR

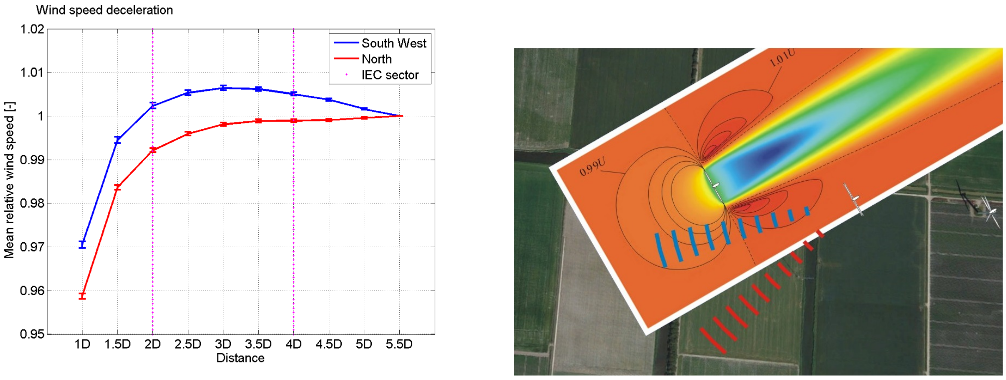
Within this task, forward and/or backward looking LiDAR capabilities on the nacelle of wind turbines for power performance and wake analysis have been subject of research. The forwards looking campaign has demonstrated the suitability of nacelle LiDARs for application in power performance assessment. It is emphasized caution should be exercised selecting undisturbed sectors, taking into account the divergence of the beams. Wake location of nearby turbines could clearly be identified. The backward looking LiDAR allowed investigation of wake recovery along the wake centerline, quantifying its dependence on operational and inflow conditions. Generally speaking a good correlation to simulations was found. To obtain more details of the wake (e.g. wake expansion, meandering) it is recommended to use a scanning or multiple beam LiDAR on the nacelle.

3.3.1 Approach

The Wind Iris from Avent LiDAR Technologies was installed on the nacelle of research turbine N6, see also Figure 1. A forward (two horizontal beams inclined at $\pm 15^\circ$ to the nacelle direction) and backward looking campaign (only center beam aligned with nacelle direction) were performed. The backward looking campaign was complimented with a Zephir LiDAR featuring a conical scan pattern at $\pm 30^\circ$ to the nacelle direction.

3.3.2 Forward looking

Turbine performance was assessed using nacelle LiDAR. As a first step the Wind Iris measured wind speed was compared to the nearby meteorological mast, where the range gate and wind direction were configured to agree with the mast location. Results are given in Figure 7(a) and more details can be found in the dedicated paper [78]. Also in the referenced paper and Figure 7(b) is the resulting power curve



(a) Relative mean horizontal wind speed against distance for both the Southwest (blue) and North sector (red) [78]. Statistical uncertainties are given

(b) Location of the lines of sight (LOS) of the Wind Iris in the vicinity of N5 for the sector 240° $\pm 5°$ [38]

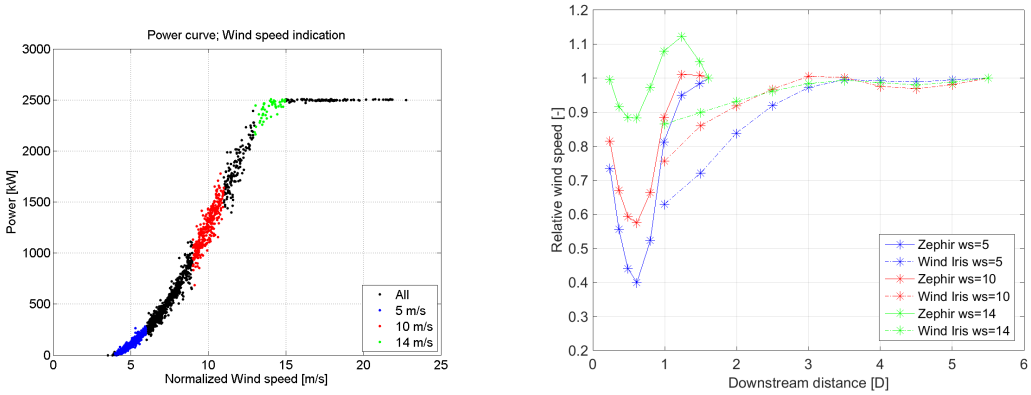
Figure 8: Measuring blockage in the 'undisturbed' sector.

comparison between the two measurement devices, showing a very good agreement.

Other topics studied are yaw misalignment, wake characterization of nearby turbines and blockage in front of the turbine. For the first topic, the Wind Iris proved a very useful tool to determine yaw misalignment (which actually amounted to 3.6° for this turbine) in a 15 days campaign with 95% confidence interval of $\pm 0.5°$. This figure was in agreement with the misalignment determined from the offset between nacelle direction (which was calibrated specifically for this campaign) and nearby meteorological mast wind direction.

Looking forward towards the wakes of surrounding turbines allowed to identify wake location by studying the standard deviation of the individual beams (radial wind speed). Amogst others, differences between the wake from a single turbines or multiple turbines were identified, owing to the different levels of wake mixing and consequently different standard deviation between them.

After a first analysis, the blockage in front of the turbine appeared to be different between the various undisturbed sectors, which has puzzled the project team (Figure 8). It appeared however that care has to be take selecting the right sectors, because the diverging beams can be within the blockage and/or upspeeding area of surrounding turbines [38]. Redefining the sector width was then shown to result in a similar blockage between the undisturbed sectors. When other turbines are around, it is advised to apply the recommended distance of 2.5 rotor diameters also for the distance between the LOS and the wake centerline of these turbines. When one of the LOS reaches within a distance of 2.5D from the wake centerline of a nearby turbine, a large up-speeding effect will disturb the measurements. More details can be found in the dedicated reports [78, 38].



(a) Power curve illustrating various wind speed ranges, 4-6m/s (blue), 9-11m/s (red) and 13-15m/s (green)

(b) Relative wind speed as function of distance for the Zephir measurements (solid) and Wind Iris measurements (dash-dotted) for various inflow wind speed ranges

Figure 9: Wake recovery in the 'undisturbed' sector [53]

3.3.3 Backward looking

To characterize the wake behind the turbine, results from the backward looking LiDARs were studied [53, 38]. The variation of non-dimensional wake recovery was plotted for various operational regimes, quantifying the influence of thrust coefficient on this important property (Figure 9). It can also be observed that the two different LiDARs connect reasonably, especially after acknowledging the Zephir conical scan to protrude outside the wake after approximately 1 diameter downstream distance. The effect of freestream turbulence intensity on the wake recovery was also quantified, confirming the large influence of this variable.

A comparison of wake centerline velocities to simulations shows a very good agreement with differences of approximately 2% for single wake conditions [38]. Here single wake denotes the wake after the instrumented turbine with undisturbed inflow conditions. Because the measurement range of the LiDAR exceeds the distance between the research turbines, also double and triple wake recovery profiles can be compared in the case of westerly wind where the instrumented turbine N6 is 'waked' by turbine N5. For double wake conditions the agreements with simulations are also quite good. However, wake effects behind the third turbine (triple wake conditions) seem to be underestimated by the Wind Iris, probably due to measurement uncertainties of the wind direction and yaw angle. To reduce these uncertainties in the future, it is necessary to measure along different LOS, for example with a scanning LiDAR, so that it will be possible to determine the real position of the wake centerline.

3.4 Task D: Wind turbine control

This section reports the achievements on the topic of wind turbine control. The main objective was to investigate the application of LiDAR for wind turbine control. In short, the following has been achieved:

- Models for the wind transfer between the LiDAR measurement and the rotor plane have been established, using both physical modelling and system identification approach. The resulting models estimate the incoming wind with sufficient accuracy to be applied for collective pitch control.
- To be able to analyze the impact of LiDAR based control on the wind turbine performance, the ECN Advanced Control Tool (ACT) has been extended with LiDAR sensors. It was found that LiDAR in principal does have significant benefits for rotor speed regulation and reduction of fatigue loads. However, availability is an issue when it comes to extreme load reduction. A solution could be to derate the wind turbine when the LiDAR measurement is not available, or a risk based strategy could be applied.
- There is a good correlation of LiDAR measurements and loads on the wind turbine rotor (blades), which can be used to optimize the wind turbine controller for load reduction.

The sections below discuss the approach and results in more detail.

3.4.1 Approach

The objectives of this task were:

- To develop a model for the wind transfer between the LiDAR measurement and the rotor plane
- To define the required specifications of the LiDAR for wind turbine control purpose
- To assess the impact of LiDAR based control on the wind turbine performance (speed/power regulation and load reduction)
- To assess the use of LiDAR for estimation of the loads on the wind turbine rotor (blades)

Outside the scope of this project is control design and evaluation with LiDAR on a real-life system.

To be able to address these topics, a campaign has been defined to perform and analyze measurement with a five beam forward looking LiDAR (Avent LiDAR Technologies prototype) on the XEMC Darwind XD115 wind turbine at the EWTW test site. The measurements have been performed during an eight months period (Oct2013-May2014). The measurement setup is described in [52, 40].

3.4.2 Results

Measurement analysis

A first analysis of the measurements has been reported in [39]. The campaign has been successful in filling the capture matrix, covering the complete wind speed range. A method, known from the field of

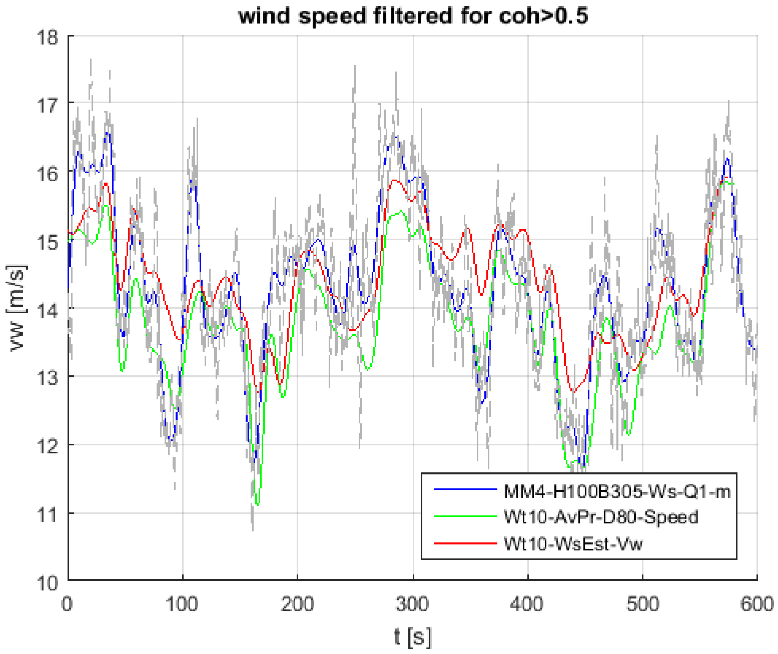


Figure 10: Time trace of the wind speed measured at the meteo mast (blue), the forward looking LiDAR at 80m range (green) and the estimated wind speed at the rotor plane (red)

wind turbine control [36], has been applied to estimate the rotor effective wind speed. This estimated wind speed is used to check correlation of the LiDAR measurements with the wind speed at the rotor plane. Figure 10 shows a time trace of the meteo mast measurement, the LiDAR measurement and the estimated wind speed, all filtered and shifted to the rotor plane. As also discussed in [39], there seems to be a clear relation between instantaneous shear loads and the LiDAR measured shear.

For a proper choice which LiDAR range gate to use as input for the controller, the cross-correlation between the measured wind and the wind turbine loads is investigated [16]. A cross-correlation provides information about the similarities in the two signals as well as the time delay between them. For the current study three range gates have been considered: 170 m, 110 m and 50 m. The first range gate provides the best estimate of the undisturbed wind speed. For the second range gate the Carrier to Noise Ratio (CNR) is the best and the third range gate is the one closest to the wind turbine. The 170 m range gate has the advantage of providing the largest preview time for a controller and the disadvantage that the measured wind can differ most from the actual wind at the rotor disc (due to wind evolution). In total 100 10-min. time series between November 2013 and April 2014 have been analysed. The result for the out-of-plane bending moment is shown in Figure 11. The range gates at 50 m and 110 m turns out to be best. Similar results are obtained for the aerodynamic torque. As expected, the correlation of the in-plane moment and the wind speed is very small since the in-plane moment is mainly determined by gravity. In the near future the results will be put in lookup tables for torque and pitch control.

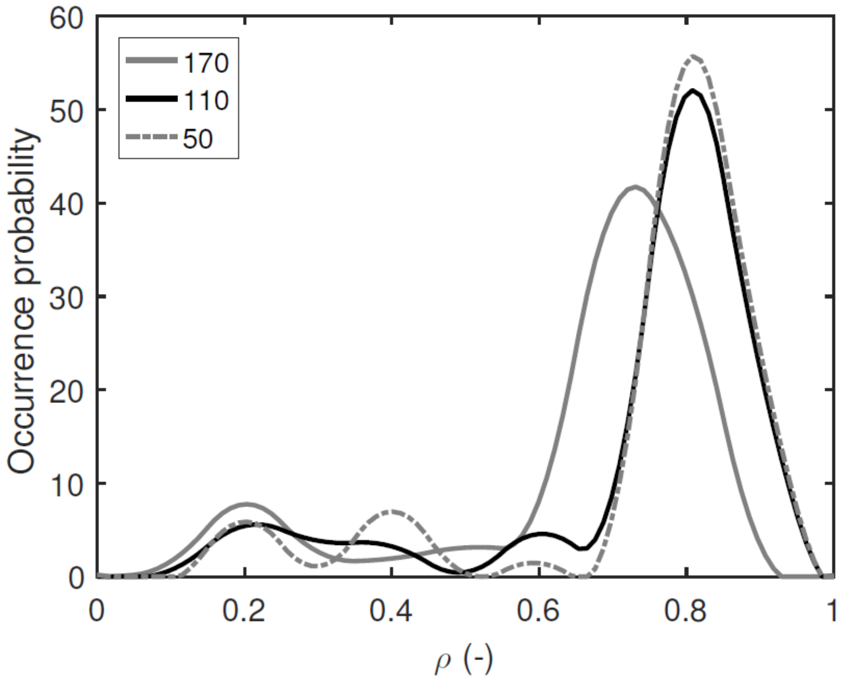
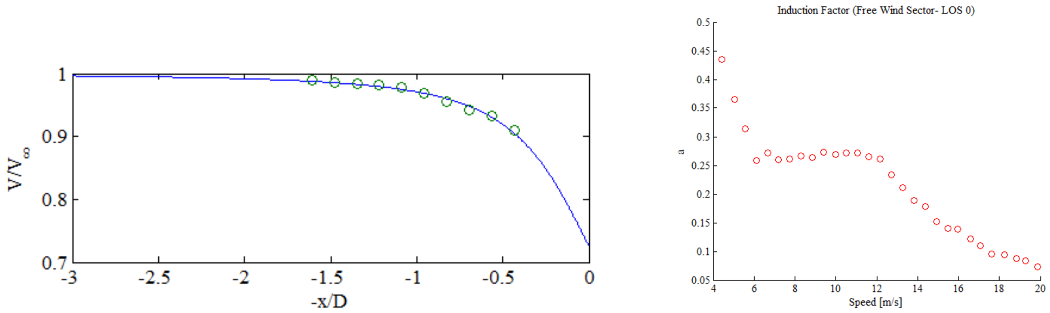


Figure 11: Effect of Lidar measurement distances on correlation between out-of-plane bending moment and the wind speed signals for 3 range gates (above rated conditions)

Wind modelling

A master thesis work by A. Abdelsalam at Avent LiDAR Technologies [7] performed a closer look to the wind transfer function between the subsequent LiDAR measurement planes ('range gates'). The blockage effect has been captures in a model, as well as the wind shear. Different methods for determination of the correlation have been tested. Important finding is that the transportation wind speed, at which the turbulent structures travel towards the rotor plane, is constant and very close to the average wind speed. The results have been presented at the DEWEK2015 conference [8]. Figure 12 shows the blockage effect of a wind turbine derived from LiDAR measurements and the calculated induction at different wind speed across the operating range.

A PhD thesis is started by A.H. Giyanani at TU Delft on modelling of the wind evolution between the LiDAR measurement and the rotor plane. At the time of writing, the thesis is about half way. A literature survey [15] has been performed on the current state of the art with LiDAR control, including the expected benefits. For a control action the wind speeds at the rotor disc should be known, in order to determine the loads. Since the control action will require some time the wind speeds should be known in advance. The wind speeds which are available are the wind speeds measured by the LiDAR at several distances in front of the rotor (excluding the blind zone, say 50 m upwind of the rotor). So a model has to be obtained



(a) Measured axial velocity as a function of the distance from the rotor (circles), together with fitted wind model to determine the induction parameter

(b) Variation of measured axial induction factor a with undisturbed wind speed

Figure 12: Blockage and induction as captured from LiDAR measurements [7]

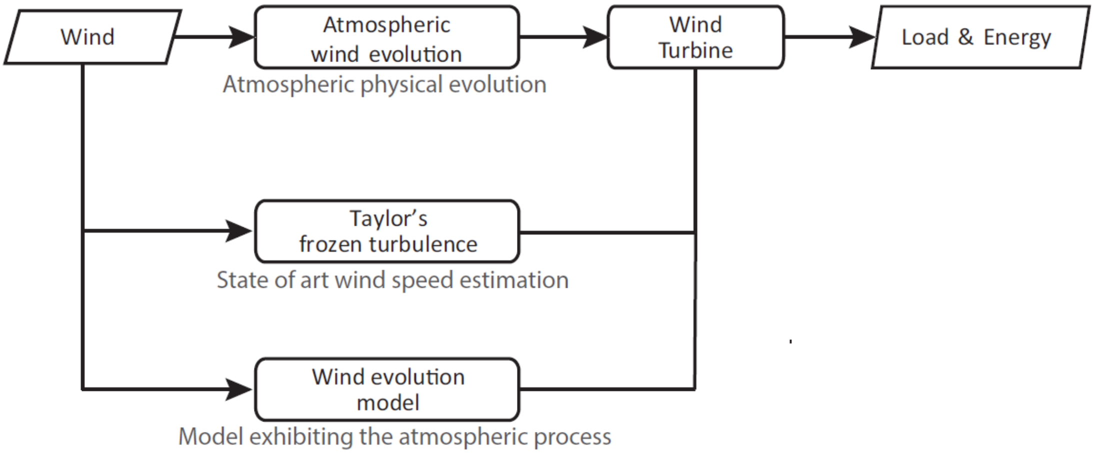


Figure 13: Process diagram illustrating the natural atmospheric process of wind evolution followed by two different approaches to resemble the modelling of this process, namely by Taylor's frozen turbulence assumption or using a wind evolution model. The latter being the objective of the PhD study, from [15].

which predicts the wind at the rotor disc based on earlier wind measurements in front of the rotor. Such a model is coined "wind evolution model" (see Figure 13). Up to now Taylor's frozen turbulence hypothesis is used in wind turbine control; this hypothesis states that turbulence travels unchanged to the rotor disc. The literature study addresses amongst others the method of Bossanyi to "unfreeze" turbulence, which is based on the eddy decay model of Kristensen [61]. In a study by Schlipf [28] a maximum wave number of k=0.125 rad/m is mentioned up to which the frozen turbulence hypothesis is a good approximation. This limit more or less equals the start of the so-called inertial subrange; this is the frequency range for which the turbulence spectrum has a slope of -5/3 (according to Kolmogorov).

The direction taken of the PhD is to apply system identification, to be specific: Autoregressive Moving

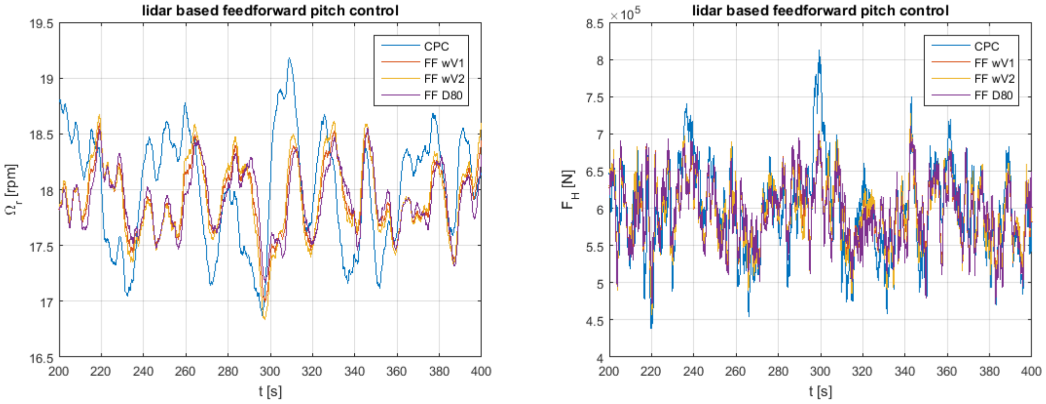


Figure 14: Wind turbine rotor speed and thrust response with LiDAR based feedforward collective pitch control featuring different weighting of the range gates (blue: no LiDAR, red: equal weighting, orange: increased weight towards the rotor, purple: single range gate at 80m)

Average Exogenous (ARMAX) models, to estimate the wind evolution model. The approach is twofold: on the one hand looking at synthetic wind fields (known input), on the other hand using the measurements from the Avent LiDAR Technologies five beam prototype LiDAR. Feedback has been given to this work from the LAWINE partners, and this will be continued in 2016. The developed model is foreseen to be used at ECN (and possibly other partners) in follow up work on LiDAR based control. The work has been presented at [20] and [22].

Wind turbine control

To be able to analyze the impact of LiDAR based control on the wind turbine performance, the ECN Advanced Control Tool (ACT) has been extended with LiDAR sensors [74]. A basic decorrelation of the wind field [32] is applied in the simulations, to get more realistic results. The focus has been on collective behavior, such as gust response and collective pitch control feedforward. A new method for weighing the range gates has been proposed, using tailored cutoff frequencies for each gate. Figure 14 shows the wind turbine rotor speed response for above rated wind speed with LiDAR based feedforward collective pitch control as simulated with ACT. Application of LiDAR feedforward control clearly reduces rotor speed and thrust variations. The figure also shows that different weighting of the range gates slightly influences the results. A inventory of specifications (such as filtering and sample time requirement) for the LiDAR looking at wind turbine control application can be found in [39].

As mentioned earlier, by scanning the oncoming wind field, any threats such as gusts can be detected early and high loads can be avoided by taking preventive actions. Unfortunately, LiDARs suffer from some inherent weaknesses that hinder measuring gusts (e.g. the averaging of high-frequency fluctuations and only measuring along the line of sight). As a solution a method is proposed to construct a useful signal from a nacelle based LiDAR [71] by first fitting a homogeneous Gaussian velocity field to a set of scattered measurements, see Figure 15. Next an output signal is determined, an along-wind force, which acts as a

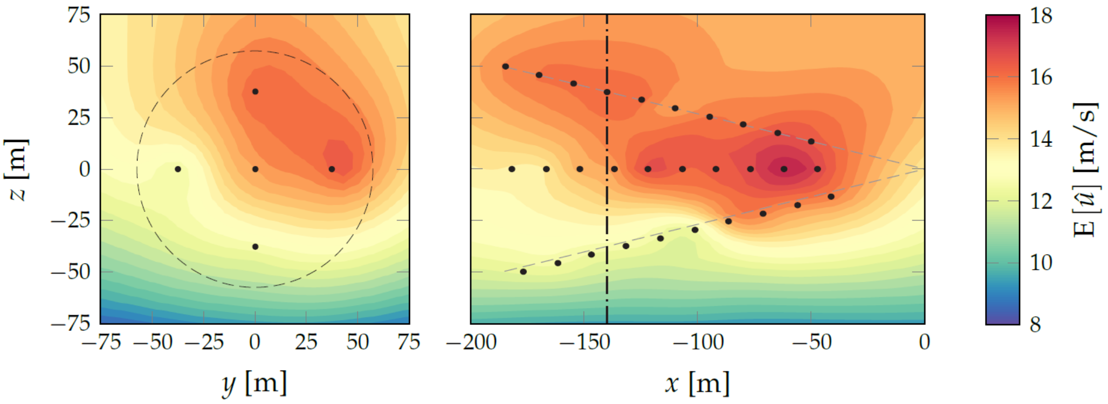


Figure 15: Stream wise mean velocity field based on one full cycle of measurements (1.25 s). The dots pinpoint the locations of the measurement points. Left: vertical plane parallel to rotor disc (140 m in front of the rotor). Right: vertical plane perpendicular to rotor disc (through rotor centre) [71].

measure for the damaging potential of an oncoming gust. Low data availability and the disadvantage of only knowing fragments of the velocity field (i.e. the dots in Figure 15) is translated into uncertainty and integrated in the output signal. This allows a designer to establish a control strategy based on risk, with the ultimate goal to reduce the extreme loads during operation.

3.5 Task E: Wind farm optimization

Within this task the application of LiDAR is researched to further optimize wind **farm** operation rather than a single wind turbine. For the active wake control concept (aiming at minimizing wake losses by actively 'steering' the wake) it was found that LiDARs can play an important role because accurate determination of yaw misalignment is of prime importance for its successful implementation. Several possibilities are distinguished to optimize the performance of a wind farm with respect to its power production. A survey is made to determine the specifications (and corresponding LiDAR technology) needed for wake location determination as input to active wake control.

For the flight leader concept (aiming at load monitoring across a wind farm using only a few instrumented turbines as load indicators), the added benefit of using LiDARs was not clearly signified. However due to the limited amount of LiDAR signals that could be taken into account in combination with the relative short duration measurement campaign it is recommended to have a closer look at the potential as part of a future research project, as the added value is categorically foreseen.

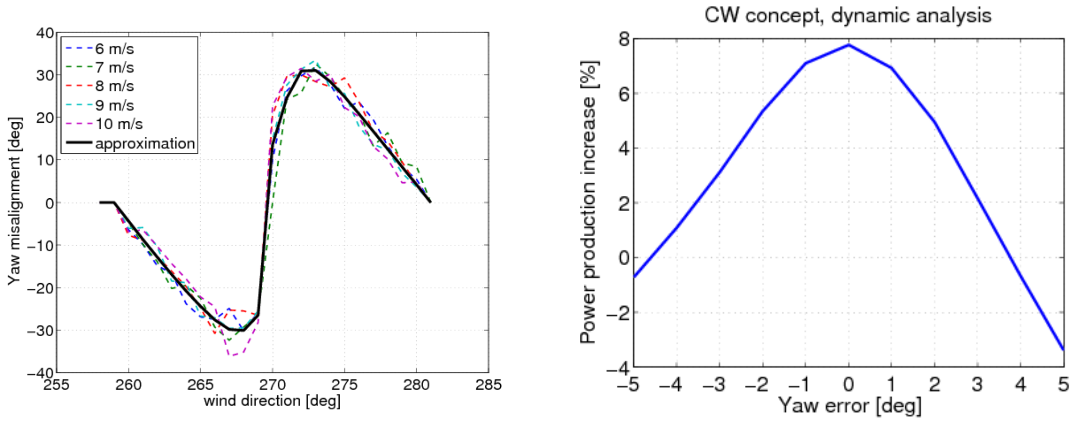
3.5.1 Active wake control

Active Wake Control is an approach of operating wind farms in such a way as to maximize the overall wind farm power production. It consists of two concepts patented by ECN: pitch-based Active Wake Control (called Heat & Flux), and yaw-based Active Wake Control (called Controlling Wind).

The idea behind the Heat & Flux concept, patented by ECN [27], is to operate the turbines at the windward side at a lower axial induction factor than the Lanchester-Betz optimum of 1/3. To achieve this, the pitch angle of the blades is increased. This reduces the power production of these upstream turbines, but the downstream turbines in their wakes get higher wind speed and make up for this power production loss, resulting in a net increase of the power output of the farm. Also the loads reduce and are more evenly distributed over the turbines.

The Controlling Wind concept, also patented by ECN [41], consists of yawing the upstream wind turbines away from the wind. Due to the resulting yaw misalignment, the wakes behind the yawed turbines are redirected aside from the downstream wind turbines, which therefore receive (a larger portion of) the undisturbed wind stream. Controlling Wind optimizes the yaw misalignment angles of each individual wind turbine in such a way, that the overall power production of the whole wind farm is maximized.

Both these Active Wake Control methods require wind speed and direction measurements to operate properly. The application of LiDAR technology to assist in and improve the execution of these concepts was studied [73]. The measurements on the research turbines located at ECN Wind Turbine Test Site Wieringermeer (EWTW) indicate that the turbines operate with a significant yaw error of around 4°, which was also confirmed in Task C (section 3.3). While this yaw error may not be significant with respect to the power production, it constitutes a very significant error when when it comes to Active Wake Control, and especially Controlling Wind, application. It is shown that such a yaw error completely destroys the whole benefit from Controlling Wind (Figure 16). Heat & Flux proves to be a more robust strategy



(a) Typical Controlling Wind settings as function of the wind direction

(b) Quasi-dynamic analysis of the effect of yaw errors on the power production gain by Controlling Wind

Figure 16: Controlling Wind settings and the effect of misalignment errors on it's benefit for a single row of seven 6MW turbines (West-East orientation) [73]

within this respect and while its benefit decreases under yaw errors, this is much less pronounced than for Controlling Wind.

Finally, a number of possible applications of LiDARs are discussed in the context of optimizing the performance of a wind farm with respect to its power production. Several options are considered, such as, (1), improving the accuracy of the wind direction measurements, (2), fine-tuning the underlying farm wake modeling (FarmFlow), and (3) using backward looking LiDARs to do online model-free Active Wake Control optimization driven by wake measurements (rather than using CFD simulations). The last option might be very promising with respect to Active Wake Control applications in wind farm in complex terrain, for which no accurate wake models with reasonable computational complexity exist.

The requirements on the LiDAR measurement equipment necessary to enable application of the proposed model-free Active Wake Control strategy have also been under consideration. It is shown that a backward looking LiDAR that measures the wind speeds at hub height in a azimuthal sector of 100 degrees suffices. But also scanning LiDARs can contribute in this field. The required resolution, however, is rather high (0.75°separation between the laser beams) to enable application in farms with larger distances between the turbines. These results, however, are just preliminary, and more detailed studies including numerical simulations are required to analyze the potential of such approach in practice. Acknowledging the high uncertainties in modeling wind farm dynamics, a demonstration campaign is highly recommended.

3.5.2 Flight Leader

The basic idea behind the Fleet Leader concept is that only a few turbines in an offshore wind farm are equipped with mechanical load measurements. These are labelled the ‘Fleet Leaders’, see also Figure 17. Using the measurements on these Fleet Leader turbines, relations should be established between load indicators and standard SCADA parameters (e.g. wind speed, yaw direction, pitch angle, etc.), which are measured at all turbines. The Fleet Leader Concept finds statistical relations between turbine SCADA data and selected load indicators by means of an artificial neural network. Once such relationships are determined for the reference turbines in a wind farm (the Fleet Leaders), these can be combined with SCADA data from the other turbines in the wind farm. This enables the determination of the accumulated loading on all turbines in the farm and this information allows the operator of the farm to prioritize maintenance [75].

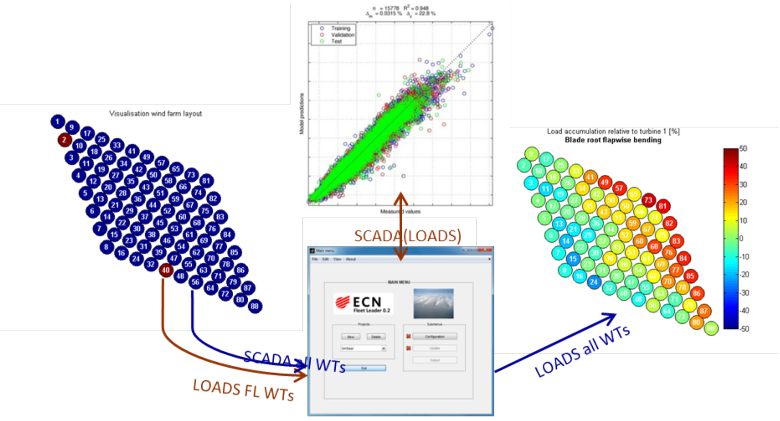


Figure 17: Illustration of Flight Leader concept

Performing a Fleet Leader analysis, a study is made to find if more accurate relations are achieved between the SCADA parameters and load indicators by including additional measurements from LiDAR (and other wind speed sources) [10]. Two studies were performed using the data from the EWTW measurement campaign. Here it is noted that only one research turbine (N6) was instrumented with load sensors. Case 1 featured a relatively small dataset of 8 months, where the training and validation of the neural network is performed for the same period and Case 2 featured a larger dataset of 2 years, where the training and validation periods are distributed into two equal halves. In both the studies, the baseline cases (without including wind speed as a training parameter) are compared with cases including the wind speed signal from either nacelle based LiDAR (Case 1 only), nacelle anemometer or meteorological mast. Two load indicators (Fatigue equivalent of Blade Flapwise and Tower Bottom Fore-aft moment) are considered for comparing the results.

For the shorter period of analysis (Case 1), it is observed that adding wind speed signal as a SCADA parameter improves the correlation marginally and thereby reduces the prediction error percentage slightly. The difference is in the range of 1-2% of error prediction. Comparing the results between anemometer,

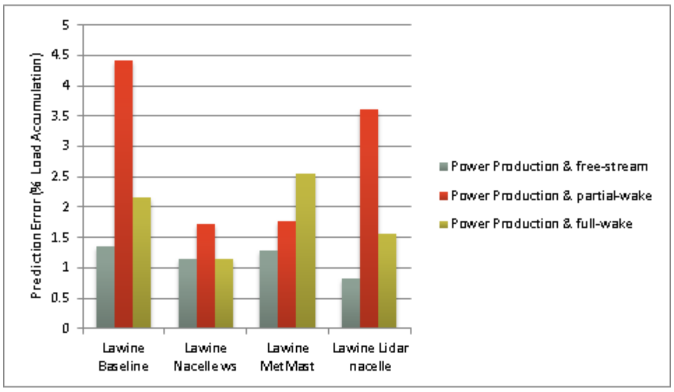


Figure 18: Prediction error of the flapwise fatigue equivalent moment in power production for the baseline and several wind speed additions, Case 1

meteorological mast and nacelle based LiDAR, wind speed measurement from turbine anemometer as a SCADA parameter provides the most convincing results. For the longer period of analysis (Case 2), it is observed that there is no clear trend of adding a wind speed signal either from the meteorological mast or nacelle anemometer. For one of the load indicators (Tower Bottom Fore-aft), adding the wind speed signal from the nacelle anemometer does show improved predictions (1-2% range) as compared to baseline, however, the conclusion cannot be generalized to other load indicators and all operational states (loadcases). It is observed that the percentage prediction error is higher in the longer period (2 years) of study as compared to the smaller period (8 months). Overall, the addition of wind speed measurement signal to perform the Fleet Leader load predictions marginally affects the concluding results. However, the improvement is not convincing and does not clearly signify the added value of wind speed as an additional signal for training the neural network.

The current study had access to a limited set of LiDAR data and moreover, for the longer period the dataset from the turbine was incomplete. To encourage better results and decisive conclusions, a larger dataset with complete data entries should be used for the analysis, especially when evaluating the added value of LiDAR. Another aspect of the study which can improve the results is the addition of multiple wind speed signals instead of a single measurement signal for neural network training. E.g. inclusion of wind speed at different heights for a ground based LiDAR (or to a lesser extent the meteorological mast), inclusion of radial wind speed signals at all range gates from the nacelle LiDAR to perform wake profiling in and around the wind turbine. Also having signals from a ground based LiDAR measuring wind speed at different positions, acknowledging the easy of relocation in comparison to a mast. Although these options need thorough investigation (including an experiment) as part of a future research project, the added value is categorically foreseen.

3.6 Task F: Efficiency improvement in measurement campaign

To accommodate the large measuring campaigns with LiDARs of nowadays, a complete data-acquisition package has been developed that can be used to acquire data from all kinds of devices [34]. The package has successfully been tested during measurement campaigns at the ECN test site.

The new data-acquisition package features a fully modular design, and is to be used with any kind of data-acquisition system. Furthermore it can be used with an unlimited amount of data-acquisition systems and measuring signals and is expandable without limitations due to the software architecture. Functionality can be added without changing the existing software and the data is delivered in a standard data file format.

3.6.1 Background

About 15 years ago, ECN has developed the data-acquisition software 'Dante' [79] to perform its measurement campaigns. Although the software is world class, very reliable and robust, there are limitations to the software that need to be overcome in order to be able to accommodate the measuring campaigns with LiDARs of nowadays:

- The number of channels in measuring campaigns has grown from about 60 signals for a measuring project in the year 2000 to about 400 signals in 2015, and is still growing. Amongst others due to the usage of LiDAR technology;
- The sampling frequency of the 'Dante' software is limited to 128 samples/second, which is often too low;
- The flexibility of the software is limited.

To overcome these limitations, the new data-acquisition software 'Daisy' has been developed, based on ambitious functional specifications. Amongst others, these functional specifications state that the data of every piece of hardware that delivers data on an Ethernet output can be acquired with the Daisy software package, and that there are no limitations on the number of acquired signals or on the sample rate due to the software architecture.

3.6.2 Daisy design

The architecture of the Daisy software has been based on a completely new concept. The Daisy package consists of a set of individual, independent processes, which communicate by means of message queues. We can distinguish two different types of processes in Daisy, as can be seen in Figure 19.

The Data Acquisition Processes (DAP) acquire data from the Data Acquisition Systems (DAS), and pass the data to the first Data Manipulation Process (DMP). This process manipulates (e.g. filters) the measured data and passes the results to the next DMP, which processes the data on its turn (e.g. re-sampling).

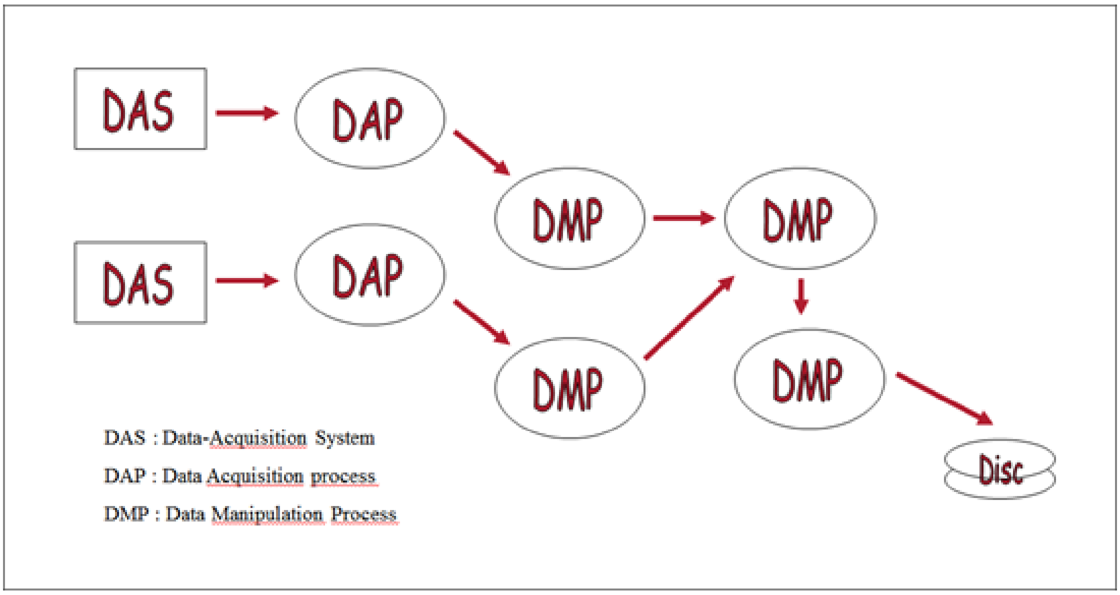


Figure 19: Main structure of Daisy

As the mentioned processes are fully independent, it is very easy to add functionality to the Daisy system: just insert a new DMP in the data-acquisition chain and you're done. Also in terms of quality this has a big advantage, as adding a new process does not influence the existing processes, and only the newly added processes need to be validated.

The result is a data-acquisition package that can literally be expanded without limits by adding new processes to the system.

3.6.3 Executed steps

To accomplish the development of the Daisy package, the below described steps have been taken.

Proof of concept test To demonstrate that the Daisy architecture works properly, and to test whether the use of message queues does not load the measurement computer, a proof of concept test has been performed. The results of the test show that the chosen architecture does not limit the amount of data that can be measured using this architecture.

Communication protocol As the processes in the Daisy package need to be able to communicate with each other, a communication protocol has been designed to be used between the Daisy processes. The protocol does not only contain ways to pass data from one process to another, but also contains commands to control one process from another.

Daisy main process As a big part of the functionality of the Daisy processes is the same for all processes, one 'mother' process has been designed from which all other processes are derived. This Daisy process is able to handle the communication with other Daisy processes, can process received data, and send the processed data to a next Daisy process.

Data manipulation processes To be able to run a measurement campaign, at least the functionality of the Dante software is needed. Therefore a number of Data Manipulation Processes have been developed that contain the functionality of the Dante software. Later, new functionality can be added by adding new Data Manipulation Processes.

Definition of data file format For the Daisy data-acquisition package, the amount of data, as well as the scan rate and the format of the data to be stored is still unknown. The data may exist of only time <-> value data, but other kinds of data might also be possible, e.g. frequency spectra, pictures, sound samples etc. Therefore a data file format has been selected that can store all of these data types in one data file. A Data Writer Process has been developed to produce these kind of data files. As the selected data file format is a standard format (hdf5), institutes from all over the world are able to handle the resulting data files.

Testing After all code was written and all processes tested individually, the Daisy package has been tested by measuring a measurement campaign in parallel with the Dante software. The output of both data-acquisition packages has been compared. A more detailed description is given in the dedicated documentation [34].

3.7 Task G: Development of European research infrastructure for ESFRI

The WindScanner.eu Prepatory Phase project has been executed in the framework of FP7. The WindScanner.eu ERIC business plan is drafted [82], together with the statutes regarding the future ERIC [81]. Stakeholders in the initiative and national node organization (including management on European level) have been involved. A proof of concept regarding database set-up and access management was created by ECN, discussed with UPorto and presented to the consortium.

3.7.1 Background

The WindScanner.eu Prepatory Phase project is executed in the framework of FP7. The project is coordinated by DTU and ECN is partner together with CENER, CRES, ForWind Oldenburg, Fraunhofer IWES, LNEG, Sintef and UPorto. Aim of the project is to build a research infrastructure with the purpose of providing highly detailed, remotely sensed wind field measurements using WindScanning equipment and to make these data available via the open access scheme. Since 2010 WindScanner.eu is on the ESFRI road map for European research infrastructures.

This project is organized in 5 workpackages[1] focusing on all relevant aspects of building such a research infrastructure.

1. Organization and Finance
2. Legal Issues
3. WindScanner Technology and Innovation
4. EERA Research Infrastructure Nodal Coordination
5. Open Access

Here, ECN is work package leader of WP5.

ECN's part of the WindScanner project is as a whole part of the LAWINE project, where WindScanner WP3 is executed in LAWINE tasks A and B and WindScanner WP1, WP2, WP4 and WP5 in LAWINE task G. WindScanner WP3 on technology and innovation is partly executed in task B as the aim of task B 3.2 explicitly is to test WindScanner equipment. Also, a part of WindScanner WP3 is executed in task A 3.1 as it is purpuse of WindScanner technology, being LiDAR based technology, to accurately measure wind fields. This section is about the achievements in WindScanner.eu WP1, WP2, WP4 and WP5 being LAWINE task G.

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[1] The 6th work package is project management and is only executed by DTU.

3.7.2 Results

In WP2 it was decided to go for an European Research Infrastructure Consortium (ERIC), which is a European entity on its own. An ERIC requires among others that national member states are partners in the facility. Therefore, ECN involved the national ministries Education, Culture and Science (OC&W) regarding structure and Economic Affairs (EZ) regarding content. A particular highlight of this workpackage is that statutes regarding the future ERIC have been drafted [81].

The main highlight of WP1 is that the WindScanner.eu ERIC business plan is drafted [82]. The plan clearly states what the objectives of the facility are. It provides the foreseen structure comprising a small central hub in Denmark and several, larger national nodes. At least 3 national nodes are required to start an ERIC. A governance structure is defined with a general assembly (highest decision making body), a board of directors (day to day management), a secretariat and the national node managers. The activities of the hub and the national nodes are defined, where the tasks of the central hub mainly are organization of training, data management and administrative tasks. The national nodes will perform the actual campaigns and make the data available. Last but not least the business plan identifies risks and presents a budget overview. In short national nodes are requested to pay a yearly fee of 40k euro. The plan is to be regarded as a selling document of the 'company' that is put up.

In addition to the WindScanner.eu business plan also a national business plan is drafted, i.e. a business plan for WindScanner.nl. As this is not yet in a mature enough phase it is not released, yet. This will come in due time.

Involving stakeholders in the initiative and national node organization (including management on European level) is part of WP4. In 2013 ECN co-organized and hosted the first WindScanner.eu stakeholder meeting in Amsterdam with representatives from the research community and from industry, both on the supplier side as on the user side. In 2014 ECN organized a national stakeholder day ”Zicht op LiDARs ” also with representatives from the research community and industry. Both meetings aimed at informing the stakeholders about the initiative and to gain feedback from them for the further development of the infrastructure.

Communications with the national ministries of OC&W and EZ have pointed out to ECN that the WindScanner.nl national node should be a widely supported research initiative. Therefore, ECN actively approached the research institutes KNMI (meteorology), TU Delft (wind energy), TNO (structural dynamics), NLR (aerospace), MARIN (marine) and TU Eindhoven (structural dynamics). Although the WindScanner.eu PP project has ended, the project still is alive. Therefore, the formation of a national node is work in progress. On European level the continuation of the initiative by the partners is assured with the signing of a memorandum of understanding.

ECN is work package leader of the WindScanner WP5 on Open Access as stated above. In that sense ECN is responsible for all 6 deliverables in the work package related to the 6 tasks

1. Database set-up and access management (ECN)

2. Scheduling of measurement campaigns (ForWind Oldenburg)
3. Data processing, validation and storing (DTU)
4. Data analysis and reporting (Fraunhofer IWES)
5. Open Access, e-Science and networking (UPorto)
6. End-user support and dissemination (DTU/CRES)

Particularly, ECN has been responsible for the first task and the report describes the details about the WindScanner.eu database set-up and how to manage the access to the database. To really demonstrate the ideas from this report a proof of concept was created by ECN, discussed with UPorto and presented to the consortium.

3.8 Task H: LiDAR Calibration Facility

A LiDAR calibration platform has been set-up at the ECN test site, both for ground based as well as nacelle based LiDARs (Figure 20). The facility was successfully demonstrated to be applicable for LiDAR calibration. A service has been developed to serve the industry.

3.8.1 Background

In the project proposal it was specified that calibration of LiDARs is a crucial part of having LiDAR technology accepted within wind energy applications. LiDAR calibration by placing a LiDAR next to a measurement mast is common practice and there is a need for further reduction of uncertainties in calibration of LiDARs. It was planned to develop and test a specially designed LiDAR calibration facility.

With respect to LiDAR calibration the following questions need to be answered [48]:

- What LiDAR systems exist?
- How should they be calibrated?
- What is necessary to do this calibration?
  - In terms of facilities
  - In terms of tools
  - In terms of accreditation

3.8.2 Approach

A LiDAR measures the line of sight (or radial) wind speed along a beam. Various of these line of sight measurements are combined to reconstruct the (for example horizontal) wind speed. In this last step assumptions may apply. In calibrating LiDARs two approaches exist. The first is the black box approach and here the eventual output of the LiDAR is compared against the reference, i.e. a wind tunnel calibrated cup or sonic anemometer. All the intermediate steps are treated as part of the black box and are not considered individually. This means for instance that validity of the assumptions made by the system, as for instance homogeneous wind field in the measurement volume, cannot be checked. The second approach is the white box calibration and in this approach all intermediate steps are calibrated. All signals relevant for the measurements etc need to be calibrated separately and this makes this approach a tedious exercise. The advantage is that assumptions are left outside the procedure.

Which approach to apply depends on the LiDAR type under consideration and may still be part of international discussions. Further details follow in the discussion of the specific LiDAR type.

- Ground based LiDARs: vertical looking LiDARs, also known as VAD scanners or wind profilers
- Nacelle LiDARs: forward (or backward) looking LiDARs placed on the nacelle or spinner of a turbine

- Floating LiDARs: ground based LiDARs placed on floaters for offshore application
- Scanners: LiDAR system with one controllable and steerable beam

3.8.3 Ground based LiDARs

The majority of the known ground based LiDARs use vertically oriented beams to measure the horizontal wind speed, direction and vertical wind speed at various heights. Several of these beams, each oriented with a small angle with respect to the zenith, are combined to reconstruct the wind speed. In this last step the implicit assumption of homogenous wind fields at these various heights is made. In flat terrain this assumption is considered to be fair and therefore it is internationally accepted to apply the black box approach for flat terrains.

In fact, this approach is to a large extent specified in official documents as for instance “IEA Ground-based vertically-profiling remote sensing for wind resource assessment” [9] and “FDIS IEC 61400-12-1 (2016) Annex L” [4] (to be referred to as Annex L). Furthermore, MEASNET has established an expert group on remote sensing and has plans to issue a MEASNET guideline on remote sensing calibration based on these documents and especially embracing Annex L. MEASNET organized the first round robins in 2015 in which ECN participated [29].

ECN further developed the service of calibrating ground based LiDARs on the ECN test facility EWTW. In order to do so it needs: (1) a calibration facility, (2) tools and procedures and (3) accreditation. To a large extent LiDARs (and also SoDARs) have already been calibrated at EWTW. However, a dedicated facility was required to further professionalize, standardize and commercialize the service. In addition, this set-up of the facility is a basis for the other LiDAR type calibrations to be treated below. This facility is established and technical described in [25]. A software tool to do the analysis is created and this software is managed according to internal ECN procedures.

Last but not least a separate accreditation for remote sensor calibration has been requested from the Dutch accreditation body ‘Raad van Accreditatie’ (RvA). This accreditation not only comprises the meteorological measurements, but also the method to validate LiDARs according to ‘Annex L’. At first instance it is focused on ground based LiDARs. The (granting of the) application is work in progress.

As part of the North Sea offshore wind conditions measurement program a ZephIR LiDAR was installed at the so-called Europlatform on May 9, 2016. In order to assure high quality measurements this LiDAR unit, i.e. ZephIR 300 LiDAR U308, was first validated and verified at the ECN LiDAR Calibration Facility for the period of February 27 until April 27, 2016. The results of these analyses are presented in [31, 30].

3.8.4 Nacelle LiDARs

The majority of the known nacelle LiDARs use forward oriented beams to measure the horizontal wind speed and direction at various ranges. Several of these beams, each oriented with a small angle with respect to the horizontal (in various directions), are combined to reconstruct the wind speed. In this last step the implicit assumption of homogenous wind fields at these various ranges is made. At high enough

(a) Ground based LiDAR calibration facility (b) Nacelle based LiDAR calibration facility

Figure 20: LiDAR calibration facility at the ECN test site

altitude this assumption is considered to be fair. However, closer to the ground this assumption is not valid anymore.

So, in calibrating nacelle LiDARs choices need to be made about the height: homogeneous wind field assumption vs stable platform and accessibility, about the method: black box vs white box, and about costs: labour intensity in relation to accuracy. A detailed description about the methods is given in [66].

Within the framework of LAWINE task C (see also section 3.3) and as part of turbine validation research and development a Wind Iris nacelle LiDAR on top of an ECN research turbine was validated against the IEC compliant meteorological mast 3. This is referred to as the black box approach from the turbine. The results have been presented in the EWEA 2014 conference and in a separate report [78, 49]. Within the framework of LAWINE task H a Wind Iris nacelle LiDAR has been calibrated according to the measurement plan [35], i.e. the white box approach from the ground and the black box approach from the ground.

To start with the latter, the black box approach from the ground did not show a good correlation with the mast [51]. Most likely this is due to the inhomogeneity of the wind field over 100m horizontal separation at a height of 23m, caused by turbulence at the surface. Both the white box approach from the ground and the black box approach from the turbine did show good correlations with the mast and in addition, it is seen that the regression results and the uncertainty values are much alike [51].

It is concluded that the white box approach from the ground is less dependent on local conditions and on the application of the LiDAR under test as compared to the black box approach from the turbine. This is considered a great advantage.

3.8.5 Floating LiDARs

Formally, floating LiDARs are not part of the LAWINE project. However, floating LiDAR has many similarities with the land based LiDAR types and the activities run in parallel. Therefore, floating LiDAR is treated here as well.

Most of the currently known floating LiDARs are ground based LiDARs placed on floating structures. Therefore, similar approaches apply as for instance black box calibration. This is internationally accepted and documented in for instance the Carbon Trust OWA roadmap [26] and recommended practices developed in the frame work of IEA task 32: LiDAR [67] and the Carbon Trust [66]. ECN has been involved in the development of both documents.

A Fugro Oceanor Seawatch floating LiDAR measurement campaign was carried out near offshore meteorological mast IJmuiden, initiated by Eneco and RWE. Here, ECN maintained the data for this campaign and the floating LiDAR was assessed according to the OWA roadmap [26] and the draft power performance norm FDIS IEC 61400-12-1 Annex L [4] are considered. The results are among others presented in [50].

Within the framework of the Carbon Trust ECN also assessed the EOLOS floating LiDAR according to the same guidelines. Both the Fugro Oceanor Seawatch and the EOLOS floating LiDAR were assessed to be second stage ‘pre-commercial’ according to the OWA roadmap [26].

3.8.6 Scanning LiDARs

Scanning LiDARs are considered to be Research and Development tools at this moment. No clear calibration procedures exist yet and the potential development of them is considered to be outside the scope of the LAWINE project. Of course, this development will closely be followed, if not picked up. This, for instance in the development of the WindScanner.eu ERIC facility [82].

4

Impact

The application of LiDAR technology has and will continue to have a large impact on the reduction of Cost of Energy (CoE) of the (offshore) wind sector. Here one can distinguish several contributions:

1. Consenting/Development – estimated 4% in cost reduction
2. Turbine and Support Structure – estimated 3% in cost reduction
3. Operation and Maintenance – estimated 4% in cost reduction
4. Gross AEP – estimated 2% in cost reduction
5. Cost of Equity – estimated >5% in cost reduction

It is beyond the scope to discuss the separate components in detail. As an example please find appendix A with a financial case study about the application a nacelle based LiDAR in order to reduce yaw misalignment. Besides CoE reduction, another aspect mentioned here is the positive effect on turnover and employment.

Two aspects measuring the impact of the specific LAWINE project are discussed separately below, namely acceptance of LiDAR technology and the development of services with LiDAR technology.

4.1 Acceptance

Since the LAWINE project started in 2012, the acceptance of LiDAR technology within the different actors of the wind energy industry has drastically and positively evolved. In 2012, Leosphere and its subsidiary Avent LiDAR Technologies had reach a global installed base of 300 units, while, early 2016, this number had increased to more than 800 units. There has been a constant growth of demand and production. The services around LiDAR technology have also evolved to a professional offer from LiDAR manufacturers and independent service providers. This is a positive sign of market acceptance and structuration to a durable use of LiDARs. The most advanced vertical profiler LiDARs like the Windcube are now integrated into best practices recommendations such as IEA Wind (the International Energy Agency) and normative standards like the Measnet, the German TR6 guideline on the assessment of the energy resource or the IEC61400-12-1 standard on the measurement of wind turbine power performance. Instrument calibration procedures have also been developed, making the LiDAR at the same level of traceability than traditional met masts. Nacelle-mounted LiDARs are also now operationally used by wind farm operators and O&M service providers in order to understand and improve their turbines performance. The improvements are noticeable with up to several percent of AEP (Annual Energy Production) obtained through a few weeks measurement campaign. Full integration of nacelle-LiDARs by wind turbine manufacturers to reduce fatigue loads of components with permanent LiDAR assisted control has also entered a new phase by some OEMs since true benefits have been emphasized in research projects, including the LAWINE project. Long-range scanning LiDARs are more recent and were introduced only a few years back. This technology offers large R&D perspectives by providing detailed information on the wind. But we also observe an increasing number of commercial projects like the assessment of the near-shore wind resource from the shore. The fast adoption of this technology is also due to the confidence gained in LiDAR technology in general. Leosphere, and its subsidiary Avent LiDAR Technologies, has observed a constant increase in the acceptance of the LiDAR technology by the wind energy industry in parallel to their continuous growth. This is explained by the fact that LiDARs have met industry requirements in terms of data quality and availability (at the same level of a met mast at least), while offering additional capacity and insight on the available wind resource and wind turbines performance, allowing stakeholders to take better decisions. The cost of LiDAR, at the beginning seen as an obstacle, is also today well-balanced with the benefits obtained by the different actors. This has contributed to the widespread acceptance of the technology.

4.2 Services

One of the goals of the LAWINE project is to develop LiDAR based services to the industry to lower the levelized cost of offshore wind energy. Several services are highlighted and detailed below.

- Wind resource assessment
    - In the project it has been demonstrated that ground based LiDAR, i.e. WindCube V2 and ZephIR 300, in flat terrain provide reliable and therefore bankable data for assessing the wind resource. A measurement campaign can be and is being offered to the industry with ground based LiDAR data as the primary source and that is the key input in a detailed wind project business case. Exploiting the advantages of the LiDAR systems, i.e. easy deployment and movability, is dependent on customer choices.
    - Although formally outside the scope of the LAWINE project, but highly connected to the matter, a framework has been put up regarding the commercial maturity of floating LiDAR systems.

    This framework is being used to offer services to the industry to assess the maturity of various floating LiDAR systems on the one hand and to offer offshore wind resource measurements, again, to make a detailed and cost effective offshore wind project business case.

- Power performance validation
  - Using ground based LiDAR for power performance assessment according to the new, draft FDIS IEC 61400-12-1 edition 2 standard has been applied and demonstrated. Outside the scope of the project procedures and software are being updated, such that after the final release of the new norm services to use this norm can and are already being offered.
  - In the project it has been demonstrated how to use a 2 beam nacelle LiDAR for power curve validation. Therefore, this is being offered to the industry to identify potential under performance (power performance verification).
- Wind farm performance assessment
  - Yaw misalignment has been assessed and observed in the project using nacelle LiDAR. This is now offered to the industry to assess the performance of all wind turbines in a wind farm.
  - For assessing the performance of a wind farm the yield is compared to the incoming wind. It has been demonstrated that ground based LiDAR assess the wind accurately. Therefore, it is now offered to the industry to perform ground based LiDAR measurements to assess the performance of a wind farm.
- LiDAR calibration The ECN LiDAR Calibration facility has been established in the project.
  - With this professionalized facility ground based LiDAR calibration services are offered to the industry for instance to perform a pre-deployment check of a system that is going to be used for wind resource assessment. In addition, the facility offers the opportunity to validate new systems on the market.
  - Using the facility a nacelle LiDAR was calibrated, where each individual step in the measurement process has been assessed: tilt, roll and line of sight calibration. This is now offered to the industry.
- Technical due diligence The knowledge and experience gained in the project is used to assist bidders that take part in tenders with respect to
  - Providing detailed and adequate information and feedback regarding the choice for equipment: ground based LiDAR, nacelle LiDAR, floating LiDAR.
  - Assessing the quality of the bidder's (instrumentation) documentation.

To bring these services to the market ECN has published two brochures

- ECN Wind Nacelle LiDAR Services [46]
- ECN LiDAR Calibration Facility [47]

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A

Financial case study: Nacelle based LiDAR

In the scope of a MSc thesis project Rik Wessels [43] has performed a financial case study about applying a nacelle based LiDAR in order to reduce yaw misalignment (YM) of wind turbines. The Prinses Alexia wind farm has been taken as example. This wind farm is installed in September 2013, and is expected to stay in operation until September 2033. It consists of 36 Senvion 3.4M104 wind turbines. In table 2 an overview of the assumptions is given. The campaign time is estimated rather conservative (compared to the 7-15 days in [78]; it takes the possibility into account that the yaw misalignment is improved in multiple steps.)

The cost of the nacelle LiDAR is assumed to be Euro 130000,-. The installation and decommissioning costs are based on required man hours and the loss of income (no electricity production) during these actions. Also O&M and data analysis have been taken into account, but these hardly contribute to the overall cost. For the benefit of a corrected yaw orientation a rather simple equation is used: the so-called Performance Improvement Factor (PIF) is calculated by:

$$\text{PIF} = 1 - \cos^2 \gamma \tag{A.1}$$

with γ the static YM. Thus for the assumed mean YM of 4° the PIF =0.49%. The result for the Net Present Value (NPV) is shown in Figure 21; as can be seen the LiDAR outperforms a spinner anemometer. Other variables commonly used in project valuation are the Internal Rate of Return (IRR) and the investment's Payback Time (PBT). The results for these variables are given in Table 3.

The results are rather sensitive for the value of the PIF; NPV breakeven is obtained for a PIF value of 0.29%. To conclude, the LiDAR investment could turn out good.

Table 2: Overview of assumptions made for the purpose of the business case

Parameter	Assumption
Remaining farm lifetime	17.5 years
Number of turbines	36
Campaign time YM correction	2 months
Electricity price	63.5 Euro/MWh
Discount rate	7.5%
Wind park availability	98%
Wind farm wake loss	5.5%
Pre-assessed wind conditions	A=7.9m/s, k=2
Average wind park YM	4°

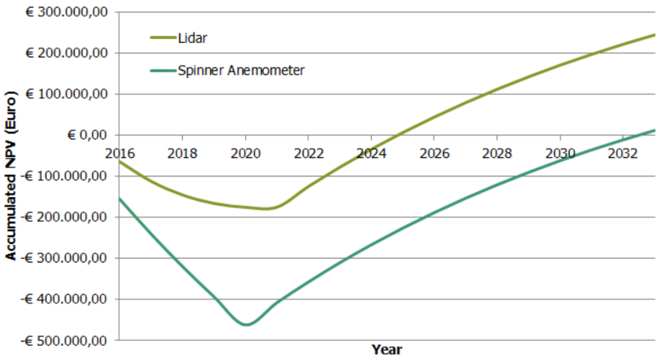

Figure 21: Development of the accumulated Net Present Value (NPV) over the lifetime of the project the LiDAR. A comparison to the result for a spinner anemometer is shown.

Table 3: Summary of economic variables

Variable	LiDAR campaign value
Net Present Value (NPV)	243 750 Euro
Internal Rate of Return (IRR)	18.5 %
Payback Time (PBT)	8.7 years

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