TIADE final report

TNO Public ❭ TNO 2024 R12112
18 December 2024

Energy & Materials
Transition
www.tno.nl
+31 88 866 50 65
info@tno.nl

TNO 2024 R12112 – 18 December 2024

TIADE final report

Author(s)	K. Boorsma, R. Giepman, A. Herrig (LM Wind Power)
Classification report	TNO Public
Number of pages	36 (excl. front and back cover)
Number of appendices	0
Sponsor	RvO
Project name	TIADE
Project number	060.39674

Summary

Within the TIADE project, 'Turbine Improvements for ADditional Energy', which ran from January 2020 to November 2024, innovative wind turbine blade improvements such as blade addons have been developed and validated to boost the performance of offshore wind turbines. The innovations developed in the project have been tested in the field on a dedicated full-scale state of the art R&D 3.8 MW wind turbine. To measure and prove the additional performance, innovative measurement techniques have been developed and applied. A worldwide pandemic and the wind industry facing large technological and financial problems made the execution of a large scale experimental program a challenging task. Despite all these setbacks, the consortium managed to successfully bring the project to an end, leading to impressive results.

- **Turbulators** have successfully been demonstrated to improve wake recovery, thereby improving farm yield with a minimal effect on loads.
- A methodology to perform **VG layout optimization** has been developed and subsequently applied in the field.
- Aero-elastic **design tool validation** has been given an impulse by using long term measurement of loads, power, deflection, noise, blade pressure and (wake) velocities under normal operational, yawed, waked and standstill conditions.
- **Mechanical and optical measurement techniques** for the accurate measurement of blade torsion and surface pressure on large wind turbine blades have been further developed and demonstrated in the field.
- The application of **swept blades** has been given a TRL-boost by dedicated wind tunnel tests of scaled-down swept blades (validating a novel sweep correction methodology for BEM) and a design study under realistic boundary conditions.
- A measurement technique for **erosion detection** in the field has been developed and applied.
- **Digital twin technology** has been progressed by the development of novel online models that can be fed by simple measurements to estimate wind turbine loads both for design and off-design conditions and reduce the time duration needed to obtain an accurate power curve.
- Along with re-scoping the project, validation of advanced **Low-Noise Trailing Edge** addons has been performed in the field, aiding the advancement of noise prediction capabilities for complex trailing edge configurations.

TIADE has been co-financed with Topsector Energiesubsidie from the Dutch Ministry of Economic Affairs under grant number TEHE119018.

Contents

1 Introduction

The challenge in offshore wind energy is to further reduce Levelized Cost of Energy (LCoE). The implementation of offshore wind power in the Netherlands is directly coupled to a required reduction of cost of energy. Even in the case, where subsidies for realising wind farms are reported to disappear, further minimisation of energy costs will have great benefits for the Dutch society. Also, costs for the grid connection are still socialised and it is required that integration in nature and integration in the energy system require additional investments. Therefore, cost reductions remain important for offshore wind power. A potential for cost reductions can still be found in blade design, and especially in the tip of the blade. Although a wide range of modelling tools exist to deal with the intricacies of the aerodynamics, it is very difficult to validate the accuracy of these tools. As a consequence it is difficult to validate the actual performance of a certain tip design.

LM Wind Power has been actively engaged in its own internal projects to improve and optimise aerodynamic performance and in particular the tips of the blades. Supported by results of own field experiments, LM Wind Power is convinced that further improvements are possible and required, especially for large scale units with very long and flexible blades. Therefore, in this project add-ons and blade tips are designed for offshore blades that further improve performance metrics. Another factor for a further reduction of LCoE is to increase the Annual Energy production (AEP) by optimization of turbine performance. The rotor or blades are “the motor” of the turbine and constitute the key enabler for increasing AEP. However, most designs of offshore wind turbines do not fully consider the fact, that these turbines are operated in large farms and suffer wake losses. Designing wind turbines with wake reduction in mind, will increase AEP of the entire wind farm, respectively improve the ratio of investment costs to energy produced.

In the TKI InnoTip project (2015-2017), two tips have been demonstrated on 2.5MW wind turbines at ECN wind turbine test site EWTW: A tip for offshore wind turbines and a tip which reduces the wake behind the turbine, which is called a ’turbulator’. With both tips, a 6% increase in power was achieved (which is more than the design tools predicted), but also a considerable increase in loads. Next to these findings, the InnoTip project showed that these tips can be used for the production of new blades and also can be retrofitted to existing turbine blades. However, the true potential of these implementations in terms of power increase is not fully understood. The impact from a blade with a turbulator on the next turbine was indecisive. It proved difficult to design tips that could easily be compared to baseline designs, since the tips had to be retrofitted onto an existing blade without a joint. A blade with a joint would remove these constraints and opens up possibilities to design blade tips with more freedom. Since the InnoTip project, the size of offshore rotors has increased even more. Rotor diameters of 220 meter and more are currently being designed. These larger diameters require better understanding of rotor aerodynamics, wake aerodynamics and aero-elastic behaviour, to increase robustness of the design. It is now a totally new design space with new uncertainties. Especially aero-elasticity is an important design driver in slender and long blades and their associated tips. One way to understand these uncertainties is through modelling tools. However, in the EU project AVATAR it was found that results from different design tools are often inconclusive. Amongst others, it was found that some state-of-the-art models predict a stable blade at standstill storm conditions, where other state of the art models predict an unstable solution, leading to failure. No measurements were available to check, which of these theoretical models is correct. Finally, the InnoTip project was focused only at the tip region of the blades. This is obviously not the only important part of the blade, as there is also potential for improvement at the root portion of the blade. Design improvements and blade add-ons should be considered, to realize full potential of the large offshore wind turbine blades and to reduce costs further. The only way of solving the above mentioned issues is by using field experiments, supported by numerical analysis and the most advanced measurement techniques. This has been done in the TKI HER TIADE project, "Turbine Improvement for ADditional Energy" [1, 2, 3], by TNO, GE Vernova (formerly GE Wind Energy / GE Renewable Energy) and LM Wind Power, which developed and demonstrated improved modelling and blade design. This project has therefore been an important next step in developing innovations in blade design and blade add-ons.

Chapter 2 provides an overview of the project organisation, including the objectives and work plan. Chapter 3 then describes the results of the different work packages, including coordination and dissemination activities, followed by conclusion and recommendations in chapter 4.

2 Project overview

2.1 Data and consortium

The high level project information is given below.

- RvO project reference number: TEHE119018
- Project name: Turbine Improvement for ADditional Energy (TIADE)
- Project consortium: TNO (coordinator), LM Wind Power, GE Vernova
- Project period: 2020/01/21 - 2024/11/30

Details about the project consortium are given in Table 2.1.

Table 2.1: Project consortium

Name of participant	Type of organisation	Role in project
TNO Wind Energy	Research and Development Organisation Non-economic activities	Coordinator **Innovations** -Innovations in tip design and add-ons -Design tool development and validation -Innovations in rotor design -Innovations in controller design **R&D Turbine** -Performing the validation experiments
GE Vernova	Industry, OEM (Original Equipment Manufacturer)	**Innovations** -Innovations in tip design and add-ons -Design and testing **R&D Turbine** -Providing R&D turbine -Supply and installation of tips and add-ons on blades -Turbine operation and maintenance
LM Wind Power	Industry, OEM (Original Equipment Manufacturer)	**Innovations** -Innovations in tip design and add-ons -Design and testing **R&D Turbine** -Supply and installation of tips and add-ons on blades

2.2 Objectives

The main objective of TIADE was to achieve a LCoE reduction of 1% by using innovative blade improvements by both design and testing of innovative tip shapes and aerodynamic add-ons to the blade surface. This LCoE reduction is realised by increasing the power production (by

2%) and / or reducing system loads by blade improvements and blade add-ons. An important objective of the project was to realise an R&D turbine at 3.8MW scale with a 130 m rotor. This turbine is dedicated to this project and provides a solution for validating and testing intrusive innovations on wind turbines. It is essential that the R&D turbine for this project is installed and operated on a location where changes to the rotor are allowed, to ascertain that the intended tests can be and will be performed.

The innovations that were planned to be developed in this project are:

- Innovative tip with new airfoils and add-ons (LM Wind Power)
- Vortex generators in combination with turbulator and root spoiler (TNO)
- Innovative tip in combination with innovations in root area (GE Vernova/LM Wind Power)
- Innovative tip with aero-elastic tailored tip (LM Wind Power/TNO)
- Long-term measurement of loads, power, aerodynamics for validation purposes
- Measurement of meteorology and wake characteristics for validation purposes
- Demonstration of innovative measurement technology
- Dedicated experiments such as large yawed operation, measurement of rough blade-surface conditions and vortex induced vibrations experiments.

Due to a variety of circumstances, it was not possible to test all the originally planned innovations. A scope change was therefore applied, refocusing the consortiums attention (see section 3.1.1 for a more detailed description).

2.3 Work plan

The project consists of four work packages. The corresponding work descriptions are highlighted below in more detail.

WP1: Project Management [In-kind]
(TNO)
WP1 is devoted to coordinating the project, administration and reporting and ensuring the technical consistency and convergence towards the main objectives. In particular, the WP aims to

- Ensure the strategic and operational management of the project
- Interface with RVO
- Provide financial and contractual management of the Consortium, including maintenance of the Grant Agreement and the Consortium Agreement

WP2 Innovations in measurement technology and applications
(TNO (WP-lead), GE Vernova, LM Wind Power)
A prerequisite to perform the measurements and tests described in this project is the availability of an R&D turbine. The blade innovations that are developed in this project still have large uncertainties in aerodynamic performance and in the associated technical risks. These uncertainties are addressed by the experiments for which new and innovative measurement technology is developed. The implementation of split blades is a key innovation and a unique enabler that allows testing and validating aerodynamic designs and add-ons in full scale. A split blade allows the installation of sensor techniques that cannot be applied to standard non-split blades. On top of that, strain gauges in the blade joint could give valuable insight in the performance of the tip. Next to this, the experiments are not possible on commercially operated wind turbines because the experiments pose additional loads to the turbine and have a relatively large risk profile. Also, installation and testing will lead to significant turbine downtimes which are not acceptable for commercial wind farms. Therefore, the partners GE Vernova and TNO planned to utilize a dedicated research turbine for the entire project. The work activities include

- Installation of the R&D turbine
- Preparation of split blades for testing of blade tips
- Development of innovations in measurements on large and flexible blades
- Installation and operation of measurement equipment
- Dismantling of the R&D turbine

Specific measurement campaigns address severe uncertainties in blade design and turbine operation, such as yaw misalignment, erosion measurements and standstill vibrations.

WP3 Innovative blade tips and add-ons including testing and validation
(LM Wind Power (WP-lead), GE Vernova, TNO)

WP3 consists of a series of developments of innovative blade tips and blade add-ons that are designed, produced and tested on a 3.8MW wind turbine. The tests require large modifications to the R&D turbine blades. By analysis of measured data the validation is performed. Most modifications are related to the tip of the blade, such as innovative airfoil tips (also incorporating pressure measurements), an aero-elastic tailored tip and turbulators. Other modifications are the application of blade add-ons at the root such as vortex generators. The experiments will be alternately guided by GE Vernova and TNO. As the results of the experiments become available these will be used to increase the efficiency of the subsequent tests and model improvements.

An illustration of the resulting project plan as originally submitted to RvO is given in Figure 2.1.

WP4 Dissemination and Exploitation [In-kind]
(TNO (WP-lead), GE Vernova, LM Wind Power)
Dissemination of results will be done as in-kind contribution to the project and consists of:

- Press release about the project

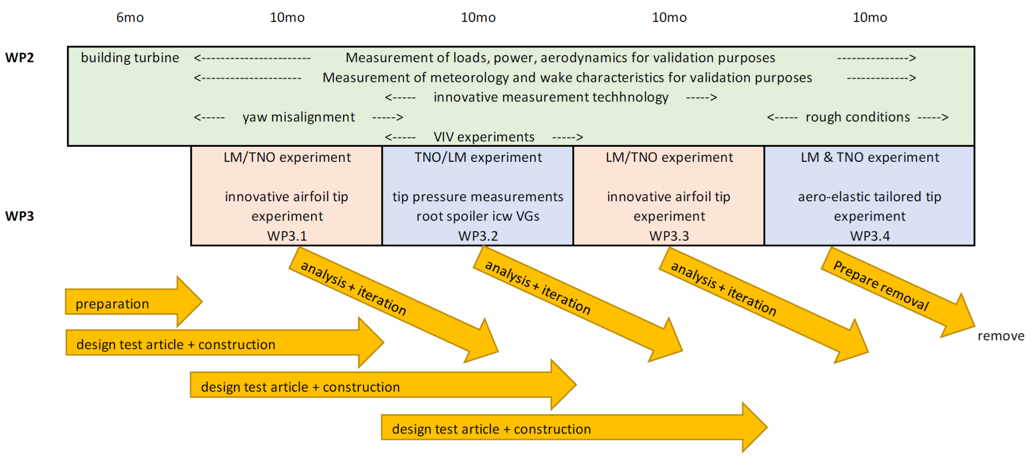


Figure 2.1: Overview of project plan as originally submitted to RvO

- Conference contribution (2x)
- Scientific publications (2x)

The scientific publications and conference contributions will consist of the learnings and the results of the measurement campaigns on yaw misalignment, rough conditions and vortex induced vibrations. The effects of these conditions on blade loading, power production and on the wake will benefit the scientific understanding of wind turbine aerodynamics. Exploitation of the results of the project will be done by developing blade add-ons for the GE Vernova turbines. The GE Vernova turbines will require efficient and effective large rotors, especially turbines for offshore wind farms.

3 Results

3.1 Coordination

TNO has been coordinating this challenging project. Apart from the frequent email traffic, bi-weekly online meetings were organized to facilitate cooperation between the project partners. On demand for project-critical decisions, tri-lateral steering committee meetings were arranged. Besides this, physical meetings were organized between the project partners e.g. during the project kick-off and inauguration of the turbine (Figure 3.2). But also the physical project work itself, such as installation of the turbine, measurement instrumentation, and producing blade parts, provided a point of contact between the partners. A project teamsite was established to facilitate the exchange of data and reports.

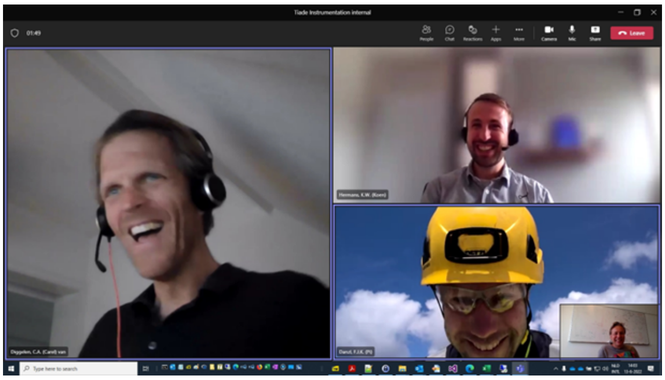


Figure 3.1: Screenshot of one of the many online meetings

(a) (b)

Figure 3.2: Inauguration of the turbine at the EWEF test site

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.

Soon after the start of the project, the COVID-19 pandemic hit Europe. As a result, cost and duration of turbine installation and instrumentation were significantly higher than planned. Amongst others, resulting sicknesses and quarantine rules, but also delays in the supply chain, contributed to this. Besides this setback, it was found already in the early phase of the project, that the original plan for incorporating a tip joint inside of a standard blade root section was not feasible, due to the limited space inside the blade. It was therefore decided to re-use a blade set that already had a tip joint in place. Because the corresponding blade length would result in a blade exceeding the allowable rotor diameter and turbine load envelope, it was decided to ”merge” the outboard part of this blade with the inboard part of another blade, and shorten it to make a 130 m diameter rotor. This ”merged blade” approach was anticipated to be the best route to realize a rotor with swappable tips suitable for installation on the available turbine platform. However, construction of the merged blades with swappable tips proved to be significantly more complex than originally expected, resulting in further cost overruns and changes to the schedule. To mitigate the impact on the schedule, it was decided to perform most of the work package 3 tasks using the readily available LM63.7 blades, for which the original turbine was designed. To that means, pressure measurements and many of the validation campaigns were already pursued with this blade set as a precursor. In addition to that, the project end date was extended to November 2024 to make up for the incurred delays.

Nevertheless, the choice for a merged blade set resulted in the use and modification of 9 already existing blades. This quantity was not budgeted for the blades themselves, neither for their transport and disposal costs. Next to this, the subcontracted costs to merge the blades had significantly increased compared to original plan. Hybrid carbon-glass scarf joint interfaces, for which no standard criteria and acceptance parameters were existing, required additional efforts for chamfer design and finite element analyses. Despite the extensive work that was performed, the structural integrity of the blades and aero-elastic stability of the resulting rotor were considered to be severe risks that could not be sufficiently mitigated. Another complication arose in the fact that the past years were extremely challenging for the wind industry. All major OEMs have faced technology, quality and financial problems, which triggered more focus on their organization and product offerings. In such context, GE Vernova and LM Wind Power had thoroughly reviewed its project portfolio and decided to pause/stop/redirect activities that presented the highest technological and financial risks. The original TIADE plan to install and operate the merged blades with tip joint was judged a severe risk landscape, hence GE Vernova decided not to proceed with it.

Without the operation of the merged blade set, some of the originally planned TIADE activities could not be carried out. Therefore, the consortium proposed to leverage the standard rotor set, to perform further tests and research to still meet the project end goal of cost reduction. The content of this scope change is described in the section below.

3.1.1 Scope change

Without having the merged blade set with exchangeable tips, operating different tip sets could not be pursued besides small scale changes to the tip of the LM63.7 blades. Although the conceptual design study of an aero-elastic tailored aft-swept blade tip could still be completed, the detailed design, manufacture, installation and field operation of the aero-elastic tailored tip had to be excluded from the project program. Wind tunnel testing of a scaled wind turbine model with and without aft-swept blade tips had been scheduled as a risk mitigation measure to ensure further progress is made on this topic. To further compensate for the scope reduction, new tasks had been proposed to fulfill the TIADE program goals and pursue LCOE reduction by leveraging the TIADE current rotor set.

- Low noise trailing edge testing
  Blade noise reduction can enable increased power/AEP respectively increased rotational speeds for a given limit, which typically translates to improved system costs from lower weight blades and drivetrain components. Further, with lower noise emissions, turbine application space can be increased, translating to market advantages. LM Wind Power has developed MkIV serrations based on an innovative design, which is substantially different from classical serration geometry. Also, its elements are modular. LM Wind Power will test the MkIV serrations on the TIADE turbine in the field, and the planned testing will help to identify an optimal configuration, while proofing fidelity of numerical prediction tools. Noise measurements are proposed in combination with power performance measurements to aid these activities.

(a) Classic Mk.III serrations (b) MkIV serrations

Figure 3.3: Illustration of different serration concepts

- Turbine digital twin
  Monitoring the wind turbine state during operational life is key to good asset management. Real-time numerical simulations ('digital twins') can provide low-cost virtual measurements for this purpose, fed by available turbine operational signals such as blade pitch angle and rotational speed. Hence instead of costly inspection and measurements, the health of the turbine can be monitored in an efficient way. In addition, it can be used to intervene in O&M decision-making, system control, and more. The TIADE turbine is an unique testbed, which has been equipped with a wide range of instrumentation, significantly more than one would install on any commercial turbine in the field. It therefore enables the TNO team to validate the capabilities of the digital twin framework and the underlying engineering models against real measurement data. A limited set of all the available sensors on the TIADE turbine will be used to see if this provides sufficient input to make accurate predictions on the loads/stresses experienced elsewhere in the turbine. The same will also be done for predicting the power output of the turbine. Special attention will be paid to non-standard turbine operating conditions, which are often not well characterized and are infamously more difficult to predict well with a digital twin. Additionally, it is often these off-design type of conditions which can have a big impact on the remaining lifetime of your turbine and which are therefore important to monitor when planning your O&M operations.

- Advanced wake decay
  The performance of an offshore wind farm depends critically upon the rate at which the low-speed wake downstream of the turbine is replenished with fresh high-energy flow. The TIADE turbine provides an excellent platform to extend knowledge in this area. TNO will measure the incoming flow and downstream flow (scanning lidar) at the same time. As such, a wake model can be built, that takes into account not only turbine

operation parameters, but also the incoming atmospheric conditions (e.g. wind profile, turbulence intensity), therefore yielding a basis for further optimizing the performance of high-density offshore wind farms. TNO has developed the FarmFlow tool [4], which has been used worldwide to optimize wind farm array layouts. The improvements will be directly implemented in this tool, ensuring application of the new findings.

Although the scope was changed, the project equally contributed to the use in 2030 and to the savings on SDE+ subsidies expenses.

3.2 WP2 Innovations in measurement technology and applications

3.2.1 Installation of the R&D turbine

Soon after project start, the foundation for the research turbine was laid: A new prototype (PT6) was installed for TIADE at Wieringermeer during the course of 2020/2021 on a new pad location. After some initial discussions, it was decided to build a 3.8 MW, 130 m diameter machine at 110 m hub height, and not go for a larger 137 m diameter rotor. In this, the tower from the former PT3 turbine (shortened by one segment), as well as components from the former PT4 turbine could be re-used. Removal of the old foundation began in May 2020, followed by casting the new foundation in September (Figure 3.4). The nacelle was assembled in Salzbergen in early Q3 2020. Changes from the former prototype (3.4 MW) to the new configuration (3.8 MW) included

- Transformer update from 10 to 20 kV middle voltage
- Generator update to a full 3.8 MW type
- Gearbox with ratio 144
- New gearbox cooler

For the Down Tower Assembly (DTA), a completely new unit was implemented. Also, state of the art controller hardware and software was installed.

As mentioned in section 3.1, the COVID-19 pandemic resulted in severe delays, impacting installation of the turbine. Furthermore, the project team faced the so-called crane ban, which is present on the EWEF test site during the winter months. This crane ban limits installation work by cranes in the winter period from November to February, not hindering bird migration. Although the tower was erected before this ban (Figure 3.5(a)), the last available weeks of October saw too high wind speeds to perform a safe installation of the blades. Also, the crane was not readily available from the previous installation at another pad in the same wind park. Consequently, the turbine had to survive the winter months until February, without the blades being suspended, which resulted in corrosion of some of the wind turbine parts. However as depicted in Figure 3.5(b), the blades could be mounted after February 2021, which started the commissioning of the turbine. From spring 2021, the turbine has been operating successfully.

3.2.2 Development of measurement innovations and installation and operation of measurement equipment

A large instrumentation campaign has been carried out on the TIADE turbine. The wind speed measurements were provided by a ground based, profiling LIDAR approximately 280 m Southwest of the turbine. In addition to that, two nacelle based LiDARs (a short and long range LiDAR, see figure 3.6(b)) and a scanning LiDAR were deployed to measure the wake of the turbine. An overview of the resulting test set-up is given in Figure 3.6(a). In addition to instrumentation largely in accordance with IEC power and loads (tower, main shaft and blades) assessment, several blade related measurement innovations were pursued.

(a) Removal of previous foundation

(b) Preparation of new foundation

Figure 3.4: Illustration of turbine foundation works

(a) Erection of tower without the blade

(b) Installation of the first blade

Figure 3.5: Installation of the turbine at the EWEF test site

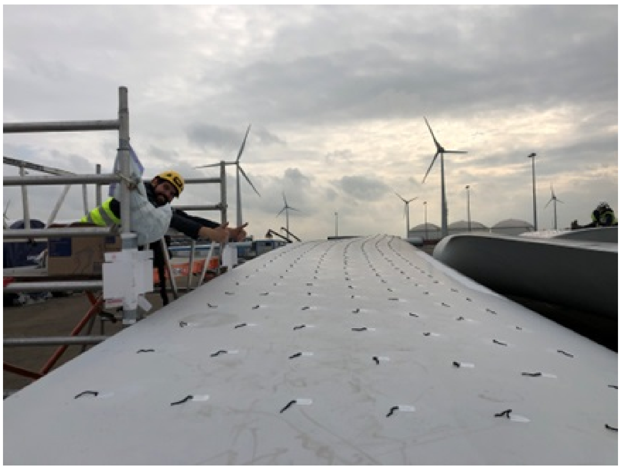
(a) Overview of test set-up

(b) Positioning of nacelle based LIDARs

Figure 3.6: Field overview at the EWEF test site

The most prominent innovative measurement technique could be considered the blade surface **pressure measurements**, to be used to monitor sectional aerodynamic performance. Published pressure measurement campaigns in the field have been carried out in the past, but very limited on large wind turbines and mostly for a short measurement duration. The harsh and rotating environment makes it difficult to have equipment functioning properly without frequent maintenance. A section 15 m from the root was selected for instrumentation with conventional tubing, still allowing access from inside the blade. Regular purging of the tubes was necessary to have them clear of water and dirt for the full length of the campaign. Accurate positioning of the holes is important together with a smooth and flush surface integration. This was attempted with a wooden template as depicted in Figure 3.7(a). Special attention was paid in advance to determine the optimal location of the pressure holes for obtaining accurate sectional aerodynamic characteristics [5]. For the merged blade set, it

(a) Wooden template for drilling of holes for the pressure measurements



(b) Application of tufts on the root section of the blades

Figure 3.7: Installation works for pressure and tuft measurements

was anticipated that a total of four spanwise sections would be instrumented with pressure taps. For the outboard sections, the limited access, long distance to the hub and the apparent vibrations would complicate a reliable routing of tubes and power. Therefore, recently developed fibre-optic pressure measurement equipment was considered as an alternative. A trial application on the LM63.7 blade set in the field revealed sensitivity of these sensors to surface strains, complicating the registration of aerodynamic pressure. With this in mind, a special purpose bushing was developed to absorb the strains and to prevent these from affecting the diaphragm [6, 7].

Tufts or woollen tell tales were applied to the inboard part of the blades before mounting them to the hub (Figure 3.7(b)). Using dedicated photography, the tufts visualize blade flow direction and separation. After the first winter period, the tufts were severely worn and they were refurbished using rope access.

Dedicated blade **torsion, strain** and **deflection** measurements were carried out on the research turbine as well. To determine the torsion deflection, a torsion rod was installed. In addition to that, an optical twist fiber was instrumented, which is a development for a less intrusive and more reliable torsion measurement technique compared to the mechanical torsion rod. However, the twist fiber could not be installed as deep in an already closed blade and showed a significant drift. The field demonstration of the TKI Vastblades project was hosted on the TIADE turbine, which included a distribution of strain measurements along the blade span

[8]. A trial was performed with the Fibersail [9] measurement system, which is an innovative technique to provide blade deflection along the blade span.

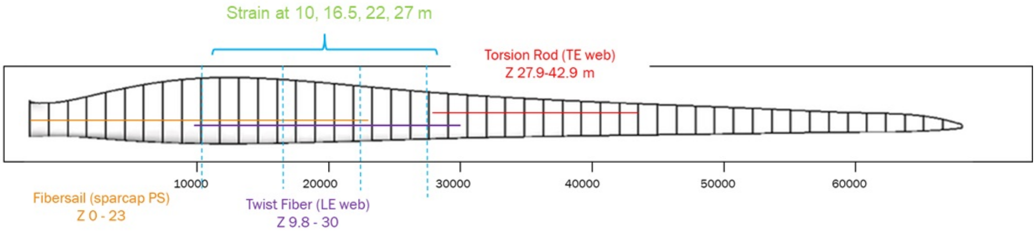


Figure 3.8: Overview of blade torsion, strain and deflection instrumentation

A detailed summary of all measurement equipment is given in the instrumentation report [10].

3.2.3 Validation campaigns

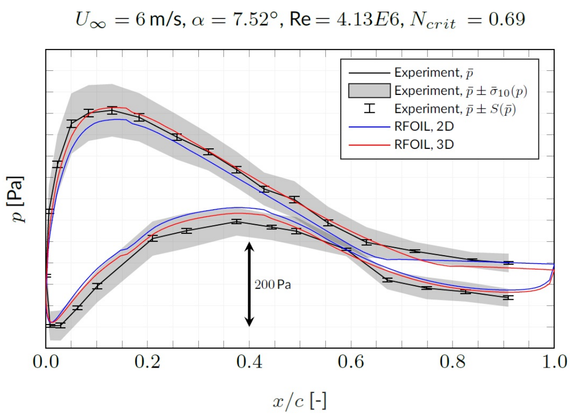
An overview of the validation campaigns can be obtained from Figure 3.9.

LM63.7 campaign		LiDARs								Blade instrumentation						Campaigns			Add-ons				
		GB WSL7	**NB-short WIGE4**	**NB-long WCN1**	**Scanning WC200S** [patterns]	**SCADA _Ct**	**Loads RW10_**	**Acc RW10_**	**Inclino RW10_**	**Pressures RW10_LM63d7_z15**	**Tufts** [pics]	**Torsion rod _TorsRodAng**	**Twist fibre _OpBlTwist_Ang**	**Deflection FBG**	**Vastblades st**	**SViV**	**Yaw-wake**	**Other**	**Serrations**	**VGs**	**Turbulator**	**LEP**	**Others**
2021	**April**						(tower/ms/blades)			(15m)	attached on ground			(fibersail)	(10,16.5,22,27m)				x MKIII				
	May										x								x				
	June	WSL7_1312 13-Jun					x 1-Jun				x	x 25-Jun		x 5-Jun	x 5-Jun				x				
	July	x					x			x (ref 1.45mm ID)	x	x		x	x				x				
	Aug	x					x			x	x	x		x	x				x				
	Sept	x					x			09-02 (ref 9&4mm))	x	x	x 28-Sep	x	x				x				
	Oct	x					x	x (2021-09-18)	x (2021-09-18)	x	x	x	x	x	x				x				
	Nov	x				x 18-Nov	x	x	x	x	x	x	x	x	x				x				
	Dec	x				x	x	x	x	x	x	x	x	x	x	7-Dec			x				x Iperman 17-Dec
2022	**Jan**	x				x	x	x	x	x	pics 20-Jan	x	x	x	x 22-Jan	31-Jan			x				x
	Feb	x				x	x	x	x	x	x	x	x	x 28-Feb		1&17-Feb			x			x 25-Jan	x
	March	x				x	x	x	x	x	x	x	x 28-March	interrogator swap					x 30-Mar			x	x 3-Mar
	April	x				x	x	x	x	x	x	x 24-Apr				7-Apr						x	
	May	x	x 19-May			x	x	x	x	x	x											x	
	June	x	x			x	x	x	x	x	refurbished 16-Jun											x	
	July	x	x		12-Jul P1	x	x	x	x	x	pics 6-Jul											x	
	Aug	x	x		P2	x	x	x	x		x									x 16-Aug		x	
	Sept	x	x	x 27-Sept	P3, P4	x	x	x	x	x	x									x		x	
	Oct	x	x 31-Oct (add sig)	x	P4, P5	x	x	x	x	x	pics 4-Oct									x		x	
	Nov	x	x	x 24 Nov check	P6, P7,P8,P9	x	x	x	x	x	x						11/12/16Nov	24-Nov hard stop		x		x	
	Dec	x	x	x	P10	x	x	x	x	x	x									x		x	
2023	**Jan**	x	x	x	P11	x	x	x	x	x 4 Jan	x									x	x 23-Jan to	x	
	Feb	15-feb	x	x	27-Feb P11	x	x	x	x		x									x	x 14-Feb	x	
	March		x	x		x	x	x	x		x									x		x	
	April	relocate 3-Apr	x	x		x	x	x	x		x									x		x	
	May	x	x	x		x	x	x	x		x									x		x	
	June	x	x	x		x	x	x	x		x									x		x	
	July	x	x	x		x	x	x	x		x									x		x	
	Aug	x	x	x		x	x	x	x		x									x		x	
	Sept	x	x	x 28-Sep 17deg up		x	x	x	x		x									x		x	
	Oct	x	x	x		x	x	x	x		x								x 17-Oct MKIV_1	x		x	
	Nov	23-nov	x	x		x	x	x	x		x								x	x		x	
	Dec		x	x		x	x	x	x		x								x	x		x	
2024	**Jan**		x 22-Jan	x		x	x	x	x		x								x	x		x	
	Feb		x	x		x	x	x (2024-02-22)	x		x								x	x		x	
	March		x	x		x	x		x		x								x 6-Mar MKIV_2	x		x	
	April		x	x		x	x		x		x								x	x		x	
	May		x	x 15-May horizontal		x	x		x		x								x	x		x	
	June		x	x		x	x		x		x								x	x		x	
	July	WSL7_127 16-Jul	x	x		x	x		x		x								x	x		x	
	Aug	x	x	x		x	x		x		x								x	x		x	
	Sept	x	x	x		x	x		x		x								x	x		x	
	Oct	x	x 15 Oct removed	x 15 Oct new test frame		x	x		x		x								x	x		x	
	Nov	x		x		x	x		x		x								x 8 Nov removed	x		x	

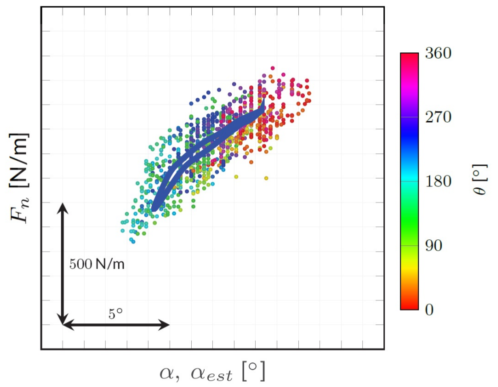
Figure 3.9: Overview of TIADE campaigns and instrumentation

3.2.3.1 Long term validation measurements

Besides the standard power and loads measurements, several other measurements were carried out as indicated in section 3.2.2. These data have been used for validation and development of aerodynamic models and remain useful for future research [11]. Some results stemming from the pressure measurements, with a unique duration of almost 2 years, are given in Figure 3.10 [12]. But also the tuft visualization proved very useful for validation purposes. Qualitatively a good agreement was obtained between measurements and simulations as shown in Figure 3.11 [13].

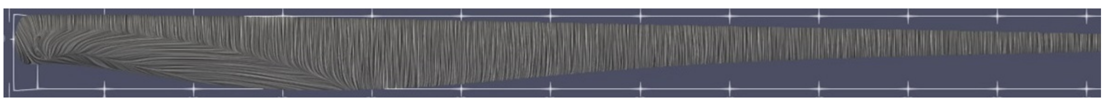


(a) Pressure distribution measured in the field compared to simulation results

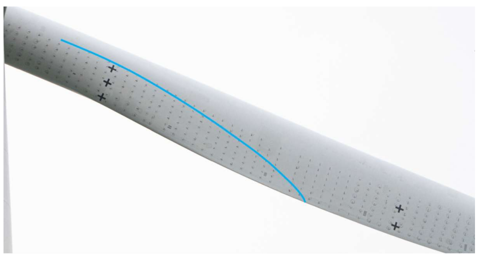


(b) Measured (dots coloured by rotor azimuth angle) and simulated (solid line) normal force as a function of the estimated or simulated angle of attack

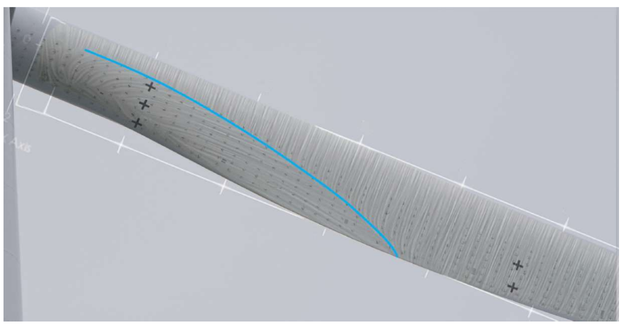
Figure 3.10: Highlighted results from long term pressure measurements [12]



(a) Simulated streamlines from CFD



(b) Tuft visualization with separation line in blue

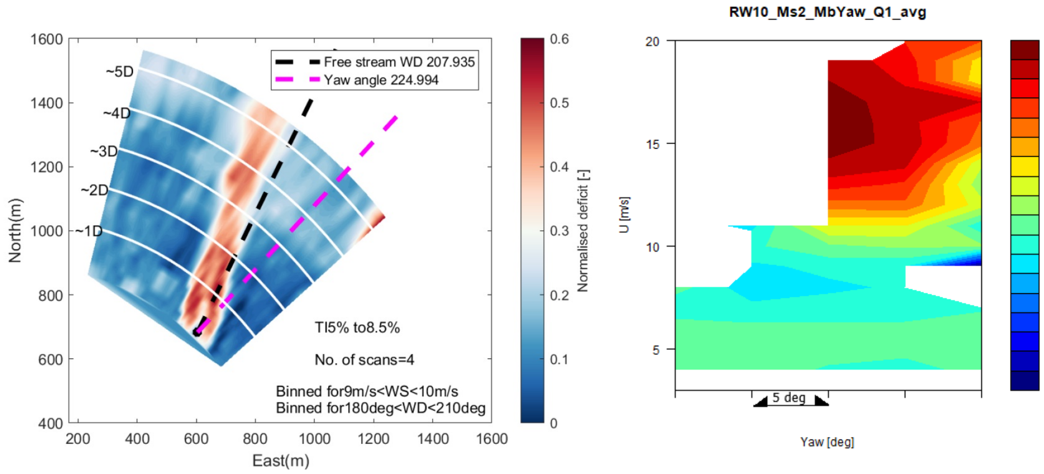


(c) Overlay of tuft and CFD results

Figure 3.11: Comparison between measured and predicted streamlines using tufts visualization and CFD simulations at 8 m/s [13]

3.2.3.2 Yawed flow

Active wake control, or the steering of wakes in wind farms by yaw misalignment of wind turbines has received much attention as a means to increase the overall power production in a wind farm. However, a large uncertainty exists in predicting wake trajectories for yawed inflow conditions. In addition to that, an individual turbine in yawed conditions will endure greater loads and will have a reduced power output, for which model predictions are uncertain as well. Besides the possibility of active wake control, yawed inflow is a frequent occurrence in normal operation. It is therefore important to know the exact extent of the effects on wake trajectory, loading and power. However, with the current models it is still difficult to predict these effects and validation on a full scale measurement campaign is needed. Hence, a yawed flow campaign was executed, where the wind turbine rotor was purposely misaligned with respect to the wind direction. A snapshot of results from this campaign is given in Figure 3.12, where data are delivered to validate design tools for safe operation of wind turbines operating with large yaw misalignment.



(a) Measured wake contours at hub height for yawed inflow conditions

(b) Measured mean of main shaft yaw moment as function of yaw angle and wind speed

Figure 3.12: Yawed flow campaign results

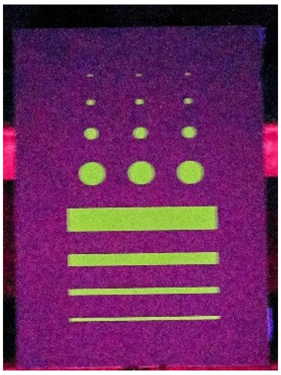
3.2.3.3 Erosion

Erosion is a critical problem in wind energy, and can result in more than 5% reduction of annual energy production. With higher tip speeds in future designs, areas with higher 'precipitation' load will increase the risk on leading edge erosion (LEE). If detection of leading edge (LE) damage is in an early phase, it is repairable with a coating repair (manual or robot), which reduces overall operational costs.

The goal of the present work was to detect and characterize small damage (tens of mm depth) on the blade LE with a minimum radius of 2.5 mm with a camera on a distance of 3-5 m using drone inspection and 30-40 m for a ground based camera [14]. For this purpose, UV fluorescent damage detection coating was used, which will improve detectability of defects in the surface layer. The penetrated top layer coating (100-150 µm) is comparable to the incubation stage of LEE damage and the fluorescent and pigmented sub layer becomes visible from the outside in case of damage. A high capacity UV light source is required and fluorescent pigment is selected for maximal reflection with the UV-A light spectrum. The application needs to be in low ambient light, as drones are not allowed to fly after sunset.

Both coating layers have been applied to the tip region of one the blades, together with a marking pattern varying from 2.5–20 mm diameter spots and bars. After a period of 6 months, where precipitation was monitored using a disdrometer, a drone campaign was performed to inspect the blades. A reference marking pattern was also applied to the tower base, which confirmed the proof of principle of the working procedure. Unfortunately, the damaged coating and markings were poorly visible after 6 months of operation, see also Figure 3.13. It was anticipated that the LE coating was completely damaged, probably due to poor quality of the coating application on site. The blade markings were also not detected, probably due to surface contamination (insects, etc.). As a follow up it is recommended to improve the

(a) Drone equipped with camera and UV-light



(b) Proof of principle using pattern at tower base

(c) Tip section with poor damage visibility

Figure 3.13: Erosion damage detection [14]

quality of coating application, but also apply a higher intensity UV beam aligned with the camera with improved focus on the inspection area on the blade. Furthermore the influence of contamination like insects on the reflection properties needs to be investigated.

In addition to techniques for the detection of damage, the effect of LEE on performance was also evaluated on a sectional level. Hereto a novel study was carried out obtaining high-resolution scans of the blade surfaces, focusing on the leading edge. The measured damage was superimposed to a clean airfoil profile to evaluate the effect on sectional performance using CFD [15], which can be used to extrapolate to turbine performance. Results from this study indicate that up to a 3.3% reduction in annual energy production (AEP) can be expected when the leading edge shape is degraded by 0.8% of the chord, based on the 5MW reference turbine. The results also suggest that under fully turbulent conditions, the degree of eroded leading edge shapes studied in this work show a minimal effect on the aerodynamic performance, which results in a negligible difference to AEP.

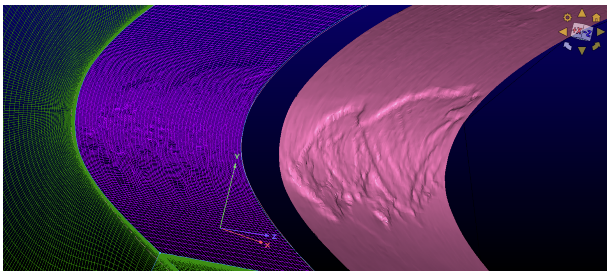
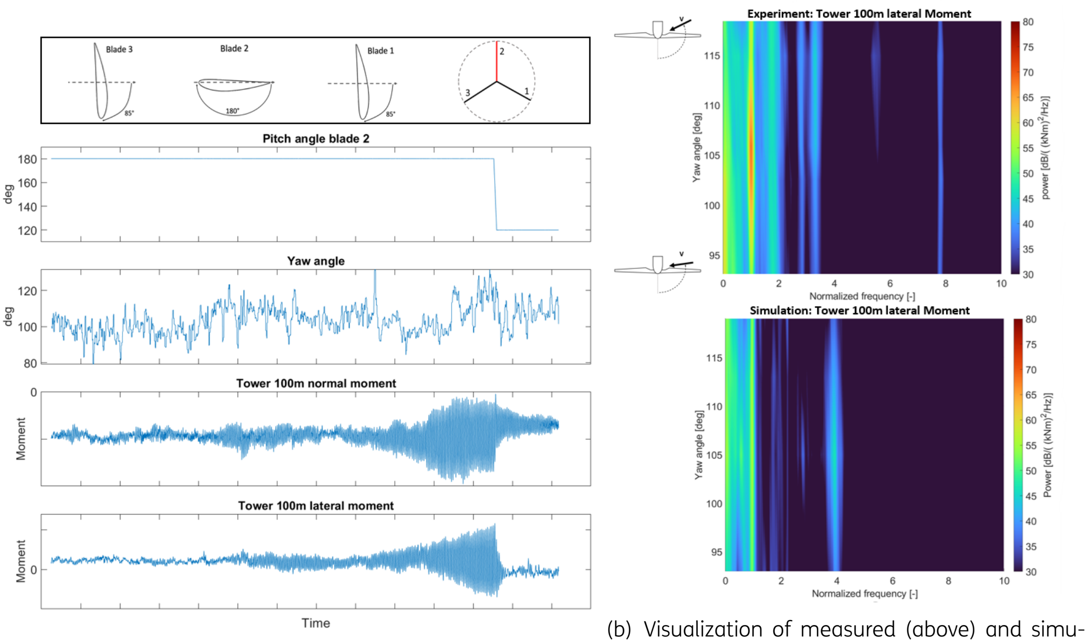


Figure 3.14: Selected portion of the scanned LE surface and its numerical grid [15]

3.2.3.4 Standstill vibrations

Modern wind turbines become increasingly flexible, and as a result more sensitive to vibrations. Currently, wind turbine vibrations at standstill are observed at high wind speeds. However, the exact conditions and sources of excitation causing the vibrations are not sufficiently understood. Knowing that farm curtailment measures will increase the period of standstill in the future, a dedicated field experiment was executed, utilizing the TIADE research turbine in parked conditions. The field measurements aimed to identify the conditions that drive vibrations for a large, parked wind turbine. To trigger vibrations of the wind turbine, a dedicated test at different pitch and yaw angles and rotor positions was performed at standstill. The measurements have been performed for wind speeds of at least 15 m/s, consisting of a pitch sweep and a yaw sweep.

First, the experimental data have been analysed to identify vibrations and the associated conditions. Next, the type of the induced vibrations was investigated. Commonly it was expected, that excitations originate from either vortex-induced vibrations or stall-induced vibrations. To assist in the identification of the measured vibrations, wind turbine aeroelastic simulations were executed in the time domain. From the analysis of the experimental data, various conditions were identified, where the measured forces were oscillating with an increased magnitude. The simulation studies confirmed the need for realistic turbulent inflow conditions and a good dynamic stall model. However as illustrated in Figure 3.15(b), capturing the measured vibrations by means of simulations is challenging and needs further research to progress the modelling [16, 17].



(a) Time series of standstill vibrations

(b) Visualization of measured (above) and simulated (below) spectra for the yaw traverse

Figure 3.15: Vibrations as measured in the yaw traverse and comparison to simulations [17]

3.3 WP3 Innovative blade tips and add-ons including testing and validation

As mentioned in section 3.1.1, not all tips could be tested and a scope change was proposed. Despite the fact that the merged blade set could not be tested on the wind turbine, a large effort has gone into the design, manufacture and instrumentation of these blades. This will be described in section 3.3.1. However, even without the merged blades, several add-ons were successfully put to the test and a conceptual design study and dedicated wind tunnel campaign were performed to advance the application of innovative swept blades tips. In addition to that, progress has been made in digital twin modelling to aid in monitoring the wind turbine state during its operational life. Also, the scanning LiDAR measurements have given new insights into accurate modelling of wake decay, which will benefit farm optimization. These innovations are described in sections 3.3.2 to 3.3.5 below.

3.3.1 Design and manufacture of merged blades

The so called 'merged blades', designed and manufactured for the TIADE prototype turbine, were comprised of 2 blade sets:

- For compatibility with the root bolt circle, former LM67.2P blades were used for the inner part. Being designed for a 137 m rotor, the stronger structure allows to keep reserves for a 130 m rotor.
- For the tip region a former LM77.4P blade set was used, which had a pin joint for tip swap capability already implemented.

The merge location was set at the location of equal chord at 34 m from the root. For blending the different airfoils on the downwind side, a short transition zone was foreseen. On the upwind side, however, larger differences in the airfoil contours and build height of the donator blades existed. This required extending an extended smoothing region, to keep the main laminate curvature low enough for structural reasons. As the main laminate materials of the two donator blade sets differed, a decision about the scarf joint materials to be used was required, for structural/adhesion compatibility, manufacturability and resulting geometry of the overlap region. The first iteration was foreseeing carbon in the scarf joint laminate. But the lack of a visual control method to exclude the presence of dry spots or air voids, respectively the high effort of performing NDT scans led to preferring glass UD laminates. This came along with a larger stacking of layers on top of the chamfered carbon main spar of the 77.4P tip portion, building up to a 26 mm high bump in the overlap zone. Checks of the aerodynamic impact were performed, indicating that the influence is minor, when the concave portions of the contour are smoothed with a filler. Hence this solution was preferred. An overview of various stages of the merge is shown in Figure 3.16.

The merge gave the possibility to include pressure and torsion instrumentation from the inside of the blade, around the transition zone. The presence of the tip joint also gave possibilities to instrument the blade tip with pressure sensors, routing the cables inside the blade. The resulting instrumentation description of the merged blades is also included in the TIADE instrumentation report [10].

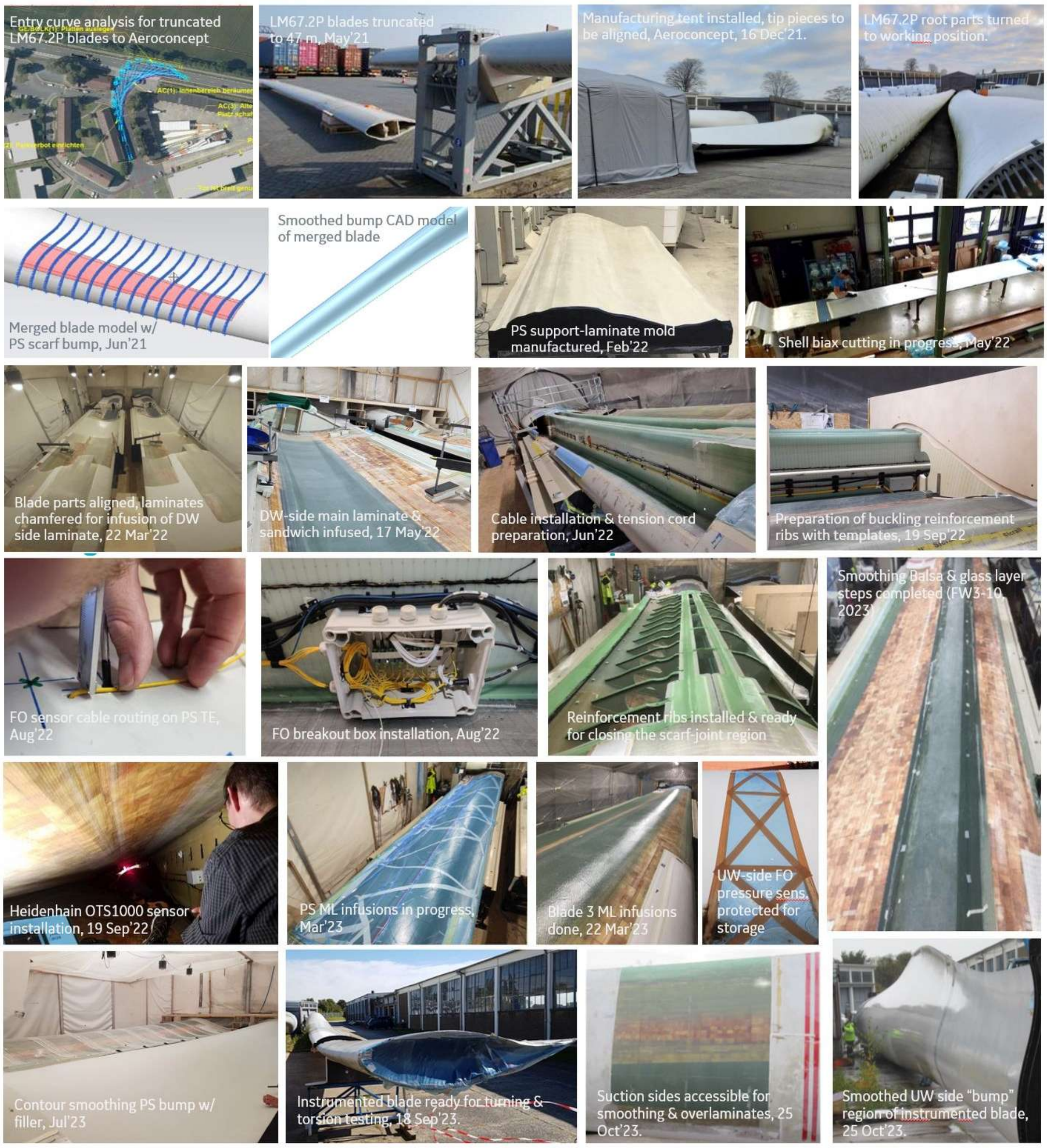
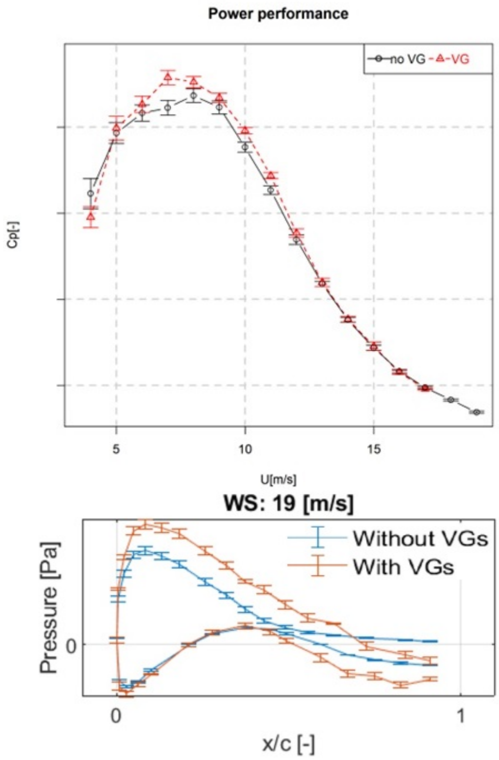


Figure 3.16: Illustration of the various stages of the merging process

3.3.2 Add-ons

Although the LM63.7 blades are equipped with vortex generators (**VGs**) by default, the TIADE test campaign started off with the blade root in 'naked' condition. This allowed to compare the performance of VGs against reference conditions and gave the opportunity to optimize the layout of the VGs. Here, the purpose of VGs is the delay of flow separation leading to a lift and hence power increase of the turbine. The installation of the VGs had to be performed uptower by means of rope access climbers, as shown in Figure 3.17(a), which was a considerable amount of work that required calm and dry weather conditions. The earlier mentioned layout optimization was performed using dedicated CFD simulations [18]. To evaluate the impact of the optimization, slightly different layouts were applied between the different blades, of which the impact on the separation line can be evaluated using tuft flow visualizaton. To aid the identification of the individual blades, these were equipped with unique marker patterns. Besides the evaluation of the impact of VGs on loads and power, also the pressure measurements can be used to verify the impact on local aerodynamics (Figure 3.17(b)) [19]. At the lowest wind speed, the local inboard angle of attack is rather low, without flow separation, and VGs are not contributing but reducing lift and hence power. However, as soon as we arrive in design operating conditions in partial load, it is clear that separation is mitigated and power production improved. Concluding, this resulted in an unique insight into the performance of VGs, which paves the way for further optimization of these popular add-ons that can be found on almost every wind turbine nowadays.

(a) Installation of VGs using rope access



(b) Measured power coefficients (above) and pressure distibutions (below) with and without VGs [19]

Figure 3.17: Visualization of the VG campaign

During the TIADE project, several noise validation test campaigns were performed, to get real-world feedback on noise performance of advanced Low-Noise Trailing Edge (LNTE) concepts such as **serrations** [20]. Overall, seven IEC standard noise tests accompanied by some non-standard measurements were performed, to evaluate potential new LNTE designs with market relevance:

- Mk.III serration prototypes (SLS-printed) and production versions (injection molded)
- Porous LNTE add-ons developed and manufactured by a TU Delft team in the frame of the IPERMAN project
- Mk.IV modular LNTE concept comprised of serration add-ons with a new, non-flat shape and downwind-side finlet add-ons, each of which could be applied individually
- Four baseline noise tests to reference the LNTE noise gains to.

Figure 3.18 illustrates a comparison between the different configurations, of which selected results have been published [20].

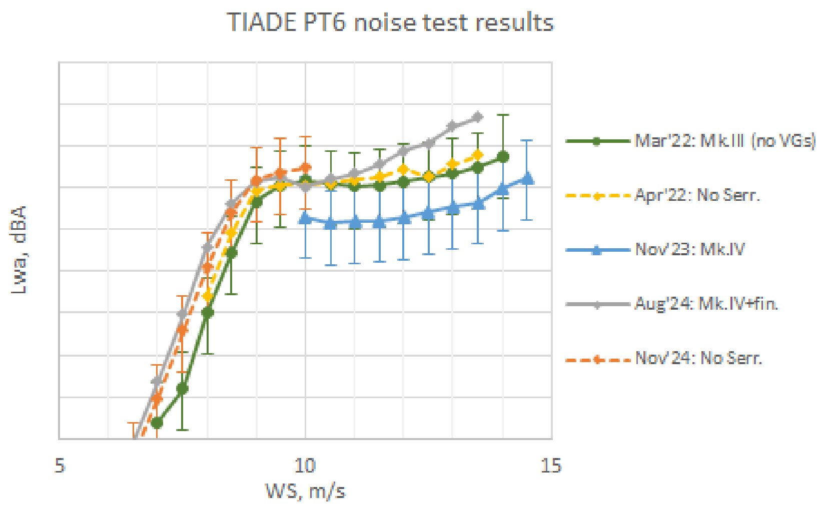
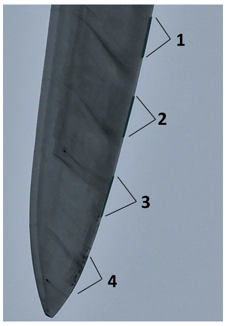


Figure 3.18: Comparison of noise measurements between different wind turbine configurations

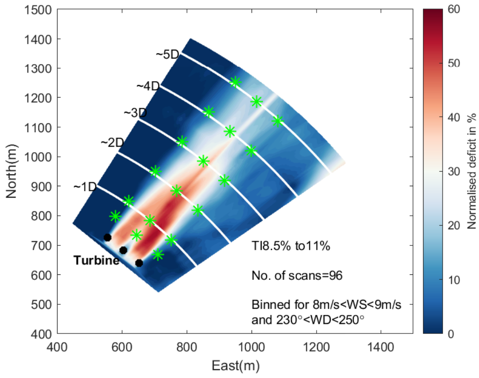
Turbulators are add-ons, proposed as a means to increase wake-mixing behind the turbine and therefore reduce wake losses in a wind farm. Based on CFD and engineering simulations, a simple design featuring segmented Gurney flaps was manufactured and installed on the TIADE turbine, see also Figure 3.19. Wake measurements using a scanning LiDAR have been conducted to assess the effect on the turbine wake. Consequently, the wake recovery was measured and compared to the baseline configuration without turbulators, together with power and loads measurements on the retrofitted turbine. A significant increase in wake speeds at all wind speed and turbulence intensity bins was measured between 1-5D downstream distance (Figure 3.19(c)) [21, 22, 23]. A small increase in turbine power and flapwise loads was measured depending on wind speed, close to the measurement uncertainty. Unfortunately the campaign was shortened due to the noise that was apparent from the add-ons. To estimate the potential of this simple add-on for boosting farm performance, the measured wake deficit improvement was inputted in a farm yield simulation tool [4], virtually applying turbulators to the turbines at the borders of Horns Rev wind farm. This exercise resulted in an impressive 0.7% increase in farm AEP. It is however recommended to perform a longer campaign to further consolidate the measured results, and to apply the add-on in a real life farm setting. Furthermore there are ideas for a Gurney flap re-design with noise mitigation in mind for onshore applications.

3.3.3 Conceptual design study of an aero-elastic tailored aft-swept blade tip

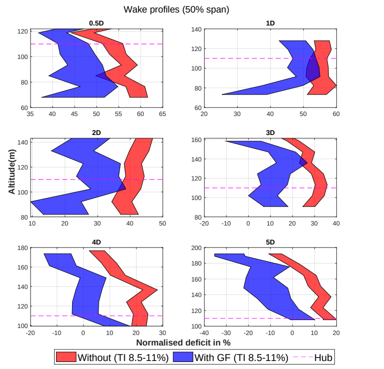
Swept blades have been studied as a means for passive load alleviation of wind turbine blades and an enabler for larger rotors. Despite the fact that this concept has been subject of investigation for many years, a widespread application has not been seen. One of the reasons is the large uncertainty associated with the aero-elastic behaviour of aft swept blades. In view of computational efficiency, wind turbine design tools are essentially still low fidelity models that struggle to accurately model other than straight blades. Therefore, an efficient blade sweep correction model for blade element momentum (BEM) theory was developed [24]. Validation of this model was performed in the wind tunnel. Therefore a set of straight and aft-swept



(a) Segmented Gurney flaps as installed on the blades



(b) Measured wake contour



(c) Comparison of vertical wake profiles for various downstream distances between configuration with (blue) and without Gurney flaps (red), 8-9 m/s bin

Figure 3.19: Visualization of results from the turbulator campaign [23]

blades were purposely designed and manufactured, based on a scaled down version of the IEA 15MW reference wind turbine [25]. Particle image velocimetry (PIV) was used to characterise the aerodynamic performance of the blades, which gives insight into sectional performance along the blade span by measuring the velocity fields around multiple radial stations. Figure 3.20 displays the swept blades and set-up in the wind tunnel. The BEM algorithm with sweep correction model has been validated using results from wind this wind tunnel campaign [26].

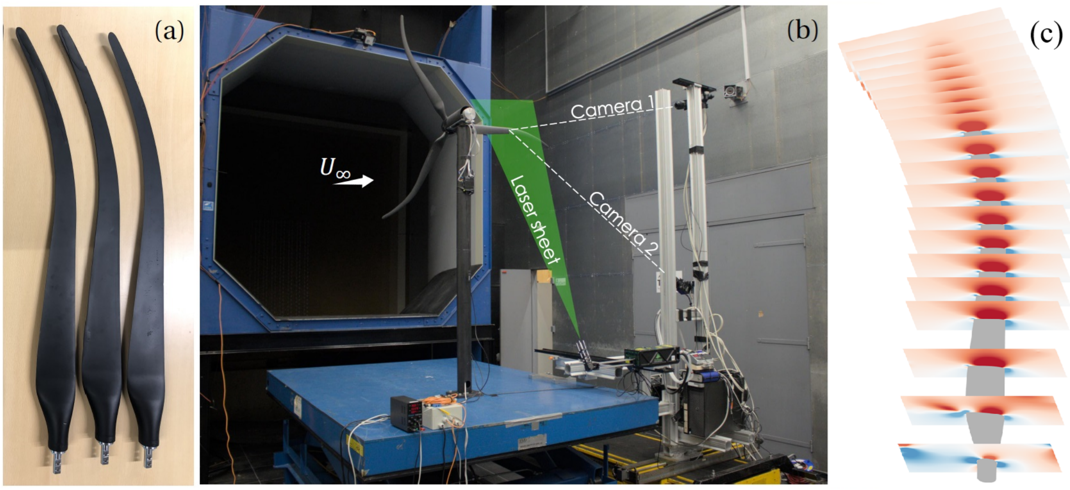


Figure 3.20: Swept model wind turbine blades (a), experimental setup and measurement system (b), and illustration of resulting PIV planes (c). The laser sheet is oriented in the plane spanned by the vertical and the inflow direction [26].

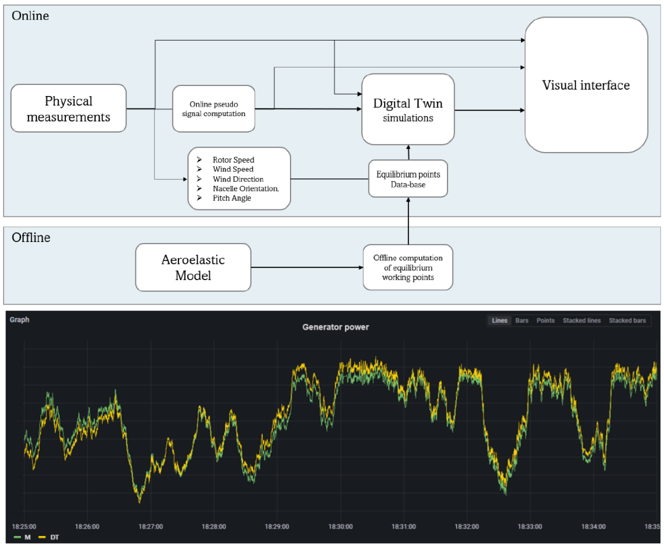
Although field operation of the aero-elastic tailored tip had to be excluded from the project program, the conceptual design study of an aero-elastic tailored aft-swept blade tip was still pursued. Within the boundary conditions imposed by the tip joints, the trade off between allowable pitching moments and fatigue load reduction was investigated together with the impact on power production [27, 28]. Based on aeroelastic simulations of design load cases 1.2 and 1.3 according to IEC standard 61400-1, the sweep-induced changes to fatigue and extreme loads at blade root, tip joint and tower bottom were evaluated. It was demonstrated that a reduction in flapwise blade root extreme loads and lifetime damage-equivalent loads of 1.0 % and 2.6 %, respectively, can be achieved when compared against a straight reference blade. At the tip joint, the relative flapwise load reductions were even larger. Torsional loads were shown to also decrease at the blade root but increase in the swept part of the blade where the coupling of bending and torsional deformations due to sweep is strongest. Edgewise loads are largely insensitive to sweeping the blade tip. Tower bottom loads also decreased, with fore-aft extreme and damage equivalent fatigue loads exhibiting the most pronounced relative reductions of 1.6 % and 2.1 %, respectively. Finally, the rotor performance was shown to hardly be affected by blade sweep. By performing this analysis in the framework of a field experiment, the relevance of the results for full-scale wind turbine blades is ensured. The outcomes corroborate the potential of swept tips as retrofit options for segmented blades or as a design choice for novel blades with decreased weight and cost.

3.3.4 Turbine digital twin

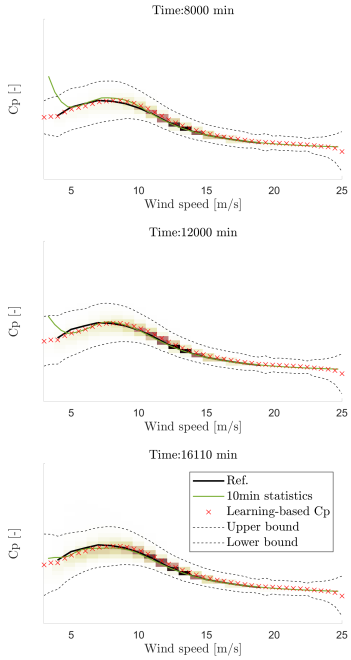
Digital twin technology has made its way into wind turbine technology, as a powerful methodology to combine measurement and models for a wide variety of applications. A number of different applications have been pursued within the TIADE project.

Real-time numerical simulations of actual wind turbine operation can be used to provide additional (virtual) measurements to better understand its performance. In addition to that, the information from the digital twin can be used to intervene in O&M decision-making, system control, and more. An online wind turbine digital twin based on a Kalman filter augmented state space Linear Time-Invariant (LTI) wind turbine model was developed for this purpose [29]. The digital twin tool was tested both offline and online, simulating and monitoring the fully functional test wind turbine. The possibility of fast virtual measurements was demonstrated, gathering and processing similarly to physical measurements of the wind turbine of interest (Figure 3.21(a)).

Another pursued application is a novel online learning algorithm for fast estimation of wind turbine power curves [30]. To accurately determine wind turbine power performance in agreement with IEC guidelines, typically several months of testing are necessary. This is a costly procedure, especially if you would like to evaluate differences between turbine configurations, e.g. the effect of add-ons highlighted in the TIADE project. By exploiting the time resolved data in combination with a learning algorithm, the necessary time to obtain a specific accuracy is reduced. The algorithm is derived based on the physical principles of the power balance between the energy available from wind and the generated electricity. A proportional-integral estimation scheme is designed on top of it to estimate the power curve from the measurement data. The developed learning algorithm is compared with the traditional 10-minute statistics and the Langevin method in a case study. The comparison results show that the proposed learning algorithm is able to estimate the wind turbine power curve more effectively within a short period compared to other methods, see also Figure 3.21(b).



(a) Workflow for virtual measurement application (above) and dashboard displaying virtual (yellow) and measured (green) generator power variation (below) [29]



(b) Comparison of power curve estimation between reference, 10–min statistics and the proposed learning algorithm for different measurement durations [30]

Figure 3.21: Digital twin applications within TIADE

3.3.5 Advanced wake decay

Measured and simulated wake properties have been compared to address the simulation-to-reality gap that currently exists in the wind turbine wake modelling. The high-resolution velocity deficit and turbulence measurements acquired through the scanning LiDAR system targeting the wake development of the TIADE turbine have been used. The measurements span both vertical and horizontal wake profiles up to five diameters (5D) downstream, offering an in-depth assessment of wake structure under diverse operational conditions. Special emphasis is placed on inflow characteristics (shear, turbulence, and atmospheric stability) due to their substantial influence on wake evolution. The results have given insight into the Stable and Neutral stratification, but miss out on the Unstable scenario due to a lack of measured data. The measured profiles are compared against results from both simulations from a parabolized Navier Stokes solver FarmFlow [4] and Unsteady Reynolds-Averaged Navier-Stokes (URANS) OpenFOAM simulations to validate model accuracy and identify areas for model refinement, in particular for the vertical wind profile within the waked region. The results of this exercise have generally shown a good agreement, see also Figure 3.22 [31, 32]. However, in some cases, a tendency from models to underestimate wake losses in both the horizontal and vertical direction of the turbine cross-section were observed. This study has improved model reliability to move towards more accurate wind resource assessments and improved wake management strategies.

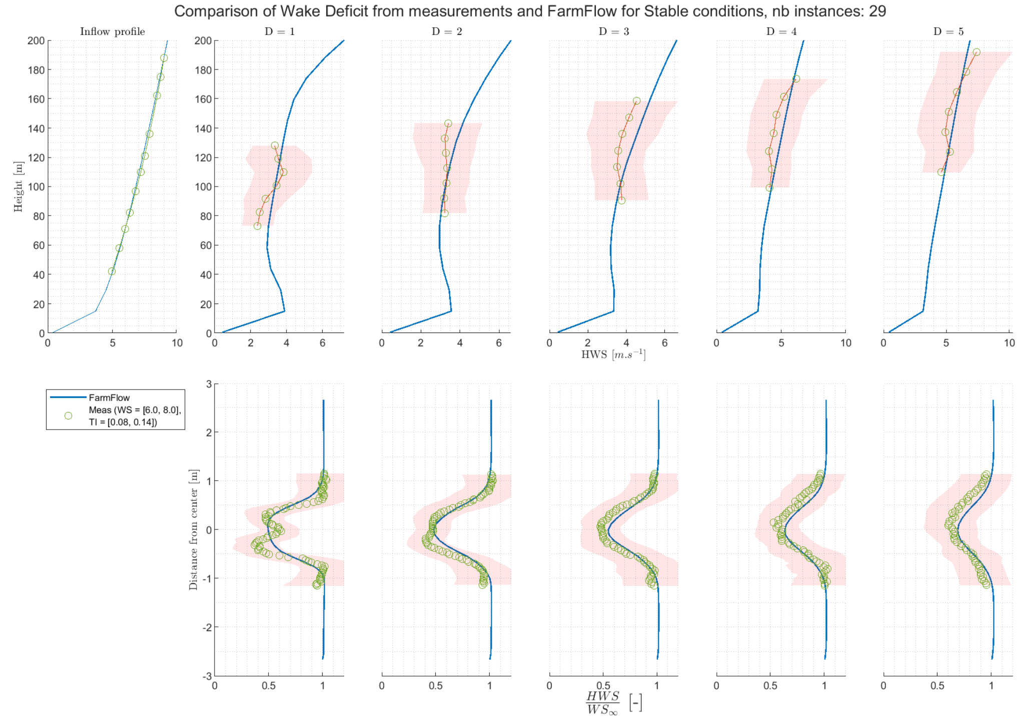


Figure 3.22: Comparison of wake deficits from measurements and FarmFlow (FF) for stable conditions. Vertical (top) and Horizontal (bottom) profiles of the wind flow downstream at 1, 2, 3, 4 and 5 diameters from the hub for measured wind speeds between 6 to 8 m/s and turbulence intensities between 9% and 13%. The red shaded area indicates the 95% (1.96*σ) confidence interval [31].

3.4 Dissemination

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
  A joint press release by TNO, LM Wind Power and GE Vernova, highlighting the project, was issued on 23 June 2021 [1].
- Conference presentations
  - Deepwind conferences [33, 16]
  - Wind Energy Sciences conferences [27, 21, 34, 7, 30]
  - Wind Europe conferences [29, 22]
    The latter submission received a best poster award at the conference.
  - NAWEA Windtech [35]
  - Wind turbine noise conference [20]
  - 4th International symposium on leading edge erosion of wind turbine blades [14]
  - Wind and Drivetrain conference [36]
  - Wake conference [32]
  - The project results have been disseminated at numerous IEA Wind Task meetings, most notably IEA Wind Task 47 [37, 38]
- Peer reviewed publications
  [24, 12, 25, 5, 28, 23, 26]
- PhD and MSc theses
  [39, 17, 19, 40]

4 Conclusions and recommendations

The TIADE project, 'Turbine Improvements for ADditional Energy', which ran from January 2020 to November 2024, has developed and validated innovative wind turbine blade improvements to boost the performance of offshore wind turbines. The innovations developed in the project have been tested in the field on a dedicated full-scale state of the art R&D 3.8 MW wind turbine. To measure and prove the additional performance, innovative measurement techniques have been developed and applied. A worldwide pandemic and the wind industry facing large technological and financial problems made the execution of a large scale experimental program a challenging task. Despite all these setbacks, the consortium managed to successfully bring the project to an end, leading to impressive results.

- **Turbulators** have successfully been demonstrated to improve wake recovery, thereby improving farm yield with a minimal effect on loads.
- A methodology to perform **VG layout optimization** has been developed and subsequently applied in the field.
- Aero-elastic **design tool validation** has been given an impulse by using long term measurement of loads, power, deflection, noise, blade pressure and (wake) velocities under normal operational, yawed, waked and standstill conditions.
- **Mechanical and optical measurement techniques** for the accurate measurement of blade torsion and surface pressure on large wind turbine blades have been further developed and demonstrated in the field.
- The application of **swept blades** has been given a TRL-boost by dedicated wind tunnel tests of scaled-down swept blades (validating a novel sweep correction methodology for BEM) and a design study under realistic boundary conditions.
- A measurement technique for **erosion detection** in the field has been developed and applied.
- **Digital twin technology** has been progressed by the development of novel online models that can be fed by simple measurements to estimate wind turbine loads both for design and off-design conditions and reduce the time duration needed to obtain an accurate power curve.
- Along with re-scoping the project, validation of advanced **Low-Noise Trailing Edge** add-ons has been performed in the field, aiding the advancement of noise prediction capabilities for complex trailing edge configurations.

Recommendations include a follow up test campaign using the readily available test-bed to further improve and finetune the existing innovations (e.g. turbulators, erosion detection) and validate newly developed innovations, of which most prominently the tip testing that could not be pursued in the first test campaign. In addition to that, the large measurement dataset that has been acquired covers many unexplored configurations and conditions. The lack of high quality validation data in the wind energy community makes this an attractive dataset, which can be further utilized to progress innovations for performance increase.

References

[1] *https://www.tno.nl/nl/duurzaam/hernieuwbare-elektriciteit/windparken-zee/innovaties-grote-windturbines-toekomst/innovatieve-windturbinebladen-testen*. accessed 29 August 2024.

[2] *https://projecten.topsectorenergie.nl/projecten/turbine-improvements-for-additional-energy-33453*. accessed 29 August 2024. 2020.

[3] *TIADE (Turbine Improvements for Additional Energy), project proposal*. Tech. rep. 2019. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP1_Management/RVO/19-09-26_HER_proposal_TIADE.pdf.

[4] E.T.G. Bot and Kanev S. *Farmflow, Extensively Validated and Dedicated Model for Wind Farm Control*. Tech. rep. TNO, 2020. URL: https://publications.tno.nl/publication/34636587/0U5yUJ/Bot-2020-Farmflow.pdf.

[5] E. Fritz, C. Kelley, and K.A. Brown. "On optimizing the sensor spacing for pressure measurements on wind turbine airfoils." In: *Wind Energy Science* 9.8 (2024), pp. 1713–1726. DOI: 10.5194/wes-9-1713-2024. URL: https://wes.copernicus.org/articles/9/1713/2024/.

[6] H. Links. *Summary of Polytech pressure sensor testing*. Tech. rep. TNO 2024 R11989. TNO, 2024. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP2_InnovationMeasurements/Instrumentation/Aero/Pressures/fibre_optic/TNO_2024_R11989.pdf.

[7] K. Boorsma, K. Hermans, and A. Herrig. "Demonstration of Advanced Blade Measurement Techniques." In: *Wind Energy Science Conference 2023*. May 2023.

[8] A.C. Veltkamp. *Resultaten van het TKI-WoZ onderzoeksproject VaStBlades naar torsiegedrag van rotorbladen van windturbines*. Tech. rep. TNO 2021 R124303. TNO, 2021. URL: https://publications.tno.nl/publication/34639022/1vdYey/TNO-2021-R12403.pdf.

[9] *https://fibersail.com/*. accessed 5 November 2024.

[10] C. van Diggelen, F.J.K. Danzl, and W.A. Castricum. *Instrumentation report TIADE research turbine*. Tech. rep. TNO 2022 R10475. TNO, 2024.

[11] L. Pergod et al. *Aeroelastic model of the TIADE turbine*. Tech. rep. TNO 2024 R1221. TNO, 2024.

[12] E.K. Fritz et al. "Blade surface pressure measurements in the field and their usage for aerodynamic model validation." In: *Wind Energy* (), e2952. DOI: https://doi.org/10.1002/we.2952. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.2952. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/we.2952.

[13] M. Caboni et al. *3D RANS-based CFD simulations on the LM637P blade*. Tech. rep. TNO 2024 M11257. TNO, Nov. 2024. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP2_InnovationMeasurements/ValidationCampaigns/Loads&PV/CFD/memo/Final_report/2024/TIADECFD_TNO-2024-M11257.pdf.

[14] H. van der Mijle Meijer. "Leading edge damage detection coating system for remote camera inspection." In: *4th International symposium on leading edge erosion of wind turbine blades*. Feb. 2023.

[15] K. Vimalakanthan et al. "Computational fluid dynamics (CFD) modeling of actual eroded wind turbine blades." In: *Wind Energy Science* 8.1 (2023), pp. 41–69. DOI: 10.5194/wes-8-41-2023. URL: https://wes.copernicus.org/articles/8/41/2023/.

[16] J. Peeringa et al. "Field experiments of wind turbine vibrations in stand still conditions." In: *EERA DeepWind Conference 2025*. Jan. 2025.

[17] M. Bouwmeesters. *Stall and vortex induced vibrations in large wind turbines*. Tech. rep. TNO 2023 M12410. TNO, 2023. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP2_InnovationMeasurements/ValidationCampaigns/SViV/TNO2023_M12410.pdf.

[18] K. Vimalakanthan. *Vortex generator layout design for TIADE blade section at 15m blade span*. Tech. rep. TNO 2024 R12151. TNO, 2024.

[19] G. Vanino. *Vortex Generators applied to large-scale Wind Turbines*. Tech. rep. TNO 2023 M12095. TNO, 2023. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP3_Tips/VG+Spoilers/report/TNO2023_M12095.pdf.

[20] G. Wang et al. "Aero-acoustic prediction tool for complex wind turbine blade configurations." In: *10th International Conference on Wind Turbine Noise*. June 2023.

[21] N.S. Dangi et al. "Segmented Gurney Flaps for Enhanced Wind Turbine Wake Recovery." In: *Wind Energy Science Conference 2023*. May 2023.

[22] K. Boorsma, N.S. Dangi, and E.T.G. Bot. "Boosting wind farm efficiency: Application of blade turbulators." In: *WindEurope 2024*. Mar. 2024. URL: https://windeurope.org/annual2024/conference/posters/PO220/.

[23] N.S. Dangi et al. "Segmented Gurney Flaps for Improved Wind Turbine Wake Recovery." In: *Wind Energy* currently under review ().

[24] E.K. Fritz, C. Ferreira, and K. Boorsma. "An efficient blade sweep correction model for blade element momentum theory." In: *Wind Energy* 25.12 (2022), pp. 1977–1994. DOI: https://doi.org/10.1002/we.2778.

[25] E. Fritz et al. "Aerodynamic characterisation of a thrust-scaled IEA 15 MW wind turbine model: experimental insights using PIV data." In: *Wind Energy Science* 9.5 (2024), pp. 1173–1187. DOI: 10.5194/wes-9-1173-2024. URL: https://wes.copernicus.org/articles/9/1173/2024/.

[26] E. Fritz, K. Boorsma, and C. Ferreira. "Experimental analysis of a horizontal-axis wind turbine with swept blades using PIV data." In: *Wind Energy Science* 9.8 (2024), pp. 1617–1629. DOI: 10.5194/wes-9-1617-2024. URL: https://wes.copernicus.org/articles/9/1617/2024/.

[27] E.K. Fritz et al. "Design of an Aeroelastically Tailored Wind Turbine Blade Tip for Field Experiments." In: *Wind Energy Science Conference 2023*. May 2023.

[28] E. Fritz, K. Boorsma, and A. Herrig. "Design of an Aeroelastically Tailored Wind Turbine Blade Tip for Field Experiments." In: *Renewable Energy* (). DOI: https://doi.org/10.2139/ssrn.4916275. URL: https://ssrn.com/abstract=4916275.

[29] M. Turrini et al. "Online application of a linear aero-hydro-elastic model for virtual monitoring of an operational wind turbine." In: *WindEurope 2023*. PO.226. Apr. 2023.

[30] Y. Liu. "Enabling fast estimation for wind turbine power curves: a physics-based online learning algorithm." In: *Wind Energy Science Conference 2023*. Nantes, France, June 2025.

[31] M. Turrini. *Advancements in Wind Turbine Wake Modelling using 3D scanning LiDAR measurements*. Tech. rep. TNO 2024 Rxxxxx. TNO, 2024.

[32] M. Turrini et al. "Advancements in Wind Turbine Wake Modelling using 3D scanning LiDAR measurements from a test turbine campaign." In: *Wake Conference 2025*. June 2025.

[33] K. Hermans. "Challenges in measuring torsion of large rotor blades." In: *EERA DeepWind Conference 2022*. Jan. 2022.

[34] M. Caboni et al. "Validation of LES inflow for predicting wind turbine loads in field conditions." In: *Wind Energy Science Conference 2023*. May 2023.

[35] E.K. Fritz, K. Boorsma, and C. Ferreira. "Unsteady Airfoil Aerodynamics based on Field Pressure Measurements of a Wind Turbine." In: *NAWEA/WindTech 2022*. Sept. 2022.

[36] K. Boorsma, F.J. Savenije, and S. Mancini. "Challenges in dynamic modeling of future wind energy systems." In: *5th Wind & Drivetrain Conference*. Apr. 2022.

[37] *https://iea-wind.org/task47/*. accessed 21 November 2024.

[38] J.G. Schepers. "IEA Task 47, Innovative aerodynamic experiment technologies and simulations on wind turbines in turbulent inflow." In: *EERA JP Wind SP4 Aerodynamics Loads & Control – FALCON 30 50 Workshop*. Feb. 2021. URL: https://zenodo.org/records/4580359#.YntqJuhBwQo.

[39] E.K. Fritz. "Swept Away, Numerical and Experimental Investigations into Swept Wind Turbine Blades." PhD thesis. Delft University of Technology, Nov. 2024.

[40] N.S. Dangi. "Segmented Gurney Flaps for Enhanced Wind Turbine Wake Recovery: Design, Field tests and Simulations." MA thesis. TNO, 2023. URL: //tsn.tno.nl/data/projects/060/3/39674/Kluis/WP3_Tips/Turbulators/Thesis_NiravSubhashDangi.pdf.

Energy & Materials Transition

Westerduinweg 3
1755 LE Petten
www.tno.nl

innovation
for life