OWA WFCT

Deliverable D6

Final Report

DEMOWIND2 Wind Farm Control Trials (WFCT)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691732

This project is funded with subsidies from the Topsector Energy by the Ministry of Economics under grant number TEHE116127.

CONTACT
James.Sinfield@CarbonTrust.com

DOCUMENT INFO SHEET

Document Name:	Final Report
Responsible partner:	Carbon Trust
Email:	James.Sinfield@CarbonTrust.com
Deliverable:	D6
Deliverable leader:	CT
Task:	T6 – Final Report following Project Termination
Task lead:	CT

DISTRIBUTION LIST

All parties involved in the DemoWind2 OWA WFCT project

APPROVALS

	Name	Company
Validated by:		
Task leader:	James Sinfield	CT
Deliverable leader:	James Sinfield	CT

DOCUMENT HISTORY

Version	Date	Main modification	Lead Author
1.0	14th February 2020	First draft	JLS and SK
2.0	18th February 2020	Comments	TV and SO
3.0	21st February 2020	Responses	JLS
4.0	6rd April 2020	Minor typos & clarifications	SK
5.0			
6.0			
7.0			

Deliverable Number	Deliverable Title	Type	Dissemination level	Due Date
D6	Final Report	Report	Public	10th March 2020

List of Contributors

PARTNER	NAME
CT	James Sinfield
CT	Stefania Omassoli
TNO	Stoyan Kanev
FNC	Trystan Glaze
innogy	Mark Osala

CONTENTS

1 INTRODUCTION

OVERVIEW OF THE PROJECT

The OWA[1] WFCT project is a project supported by DEMOWIND funding that was conceived to implement Wind Farm Control (WFC) strategies on an existing full-scale offshore wind farm and to demonstrate better lifetime economic performance through increased power production, reduced O&M costs, and increased availability and lifetime extension of existing and future assets.
Recent desktop studies undertaken by various stakeholder groups, such as FP7 ClusterDesign, FLOW program, NREL(National Renewable Energy Laboratory based in the USA) activities and other OWA projects report promising results and the WFCT trials aimed to validate these theoretical benefits on a real-life fully operational wind farm. The WFCT project was supported by wind farm developers EnBW, RWE Renewables International GmbH (formerly known as E.ON Climate & Renewables GmbH), Equinor, innogy, Shell, SSE and Vattenfall incorporating know-how from experts who have played a leading role in wind farm control concept generation and wind measurement, including DTU, TNO(formerly ECN), Frazer-Nash Consultancy and Windar Photonics.

At the project's outset it was the intention that at the selected offshore wind farm, several measurement systems would be installed; strain gauges, nine nacelle-mounted LiDARs and one scanning LiDAR. The expected increase in energy yield and load reductions were to be compared with the mathematical models, where set points (turbine input parameters) are altered and do not require any modifications to the turbine itself: this brings the enormous advantage of the control strategies being realisable on today's wind farms. However, no solid experimental evidence has yet been publicly disclosed about the performance of WFC strategies in real-life and this project aimed to validate these strategies and overall reduce the Levelised Cost of Energy (LCOE) for the operational wind farm.
Despite the wealth of evidence showing the potential benefits of this technology, the technical and economic risks pose a significant challenge for bringing this technology to market. The OWA WFCT project aimed to act as a catalyst to demonstrate WFC strategies in an operational setting to enable future adoption by the wider industry.

The ambition of the OWA WFCT project was to prove by full-scale wind farm testing that a significant improvement of the operational efficiency of wind farms is achievable in terms of increased power production, reduced Operation and Maintenance (O&M) costs, increased availability and lifetime extension.

Existing Offshore Wind Farms (OWF) at commercial scale are currently not fully optimized with respect to the efficiency of their operation; neither in terms of overall power production nor in terms of O&M costs. Turbines are operated individually, each maximizing its own power production. A noticeable improvement of the overall power production and loads

[1] The Offshore Wind Accelerator (OWA) is Carbon Trust's flagship collaborative RD&D programme. The joint initiative was set up between the Carbon Trust and nine offshore wind developers in 2008. The OWA programme aims to reduce the cost of offshore wind to be competitive with conventional energy generation, as well as provide insights regarding industry standard (and best practice) health and safety requirements.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

reduction is expected to be achievable when the wind turbines are operated in a coordinated way by a WFC algorithm. This fact was recognized in the beginning of this century and a new research area emerged aimed at the development of methods to operate the wind turbines in wind farms so as to maximize the overall power production of the whole farm and/or minimize the fatigue loading (thereby, reducing the O&M costs) on the wind turbines. Key barriers to including holistic control algorithms across an entire OWF include limitations on real time data processing as well as limited information on the behaviour of turbines in large arrays, which impacts on the modelling of such arrays. Significant advances in all three of these areas – data processing, data analysis and understanding of wake effects means that it is now theoretically possible to effectively design and implement control strategies at site. Significant research has been undertaken to understand how these control strategies can be implemented and optimised and what the likely impact of these are; with the emphasis on mathematical modelling of wind turbines and their mutual interaction . Currently, despite this body of research, there is very limited validation evidence to demonstrate that these theories work in practice. The OWA WFCT project aimed to closed this gap.

Windar Photonics A/S produces and manufactures forward-looking LiDARs which measure the wind speed in two or recently four points in space upstream of the turbine. These 'Windar WindEYE' two-beam LiDARs measure the undisturbed wind direction upstream of a wind turbine so that the turbine can be aligned or yawed very precisely into the wind. This is done is by measuring two horizontal components of the wind, one by each LiDAR beam, and then combining those to an inflow wind direction, which then is fed to the turbine yaw control system. The resulting measurements are much more accurate than estimates from traditional anemometer located on the nacelle. Furthermore, by analysing the LiDAR Doppler spectra it is possible to measure wake location with the LiDAR system which can help to characterize the flow features within a wind farm and improve the wind farm control performance.

While WFC theory exists in detail, there have been no practical demonstrations at a large scale of WFC strategies. This creates a significant market barrier as both wind farm developers, operators and owners, and wind turbine manufacturers (OEMs) will have a significant challenge to justify the perceived risk of applying these strategies without clear operational evidence regarding the benefits. Potential challenges and common concerns with applying WFC strategies include:

- Increased fatigue loads of yawing turbines. This is due to the fact that the turbines will not be facing full into the wind, which is currently generally the case, and therefore creating uneven loads on the blades. Strain gauge measurements will help understand true loads on the turbines throughout the trial, and there are many strategies which do not involve yawing.
- Validation of expected benefits. In order to get an overall increase in yield, the holistic control strategies will often sacrifice the yield of individual turbines to the benefit of the whole wind farm. To gain approval from shareholders and OEMs to deliberately down rate turbines when they could be fully loaded requires justification including clear evidence of the overall benefits. As the expected benefits are proportionally small (although relatively small margins in yield have significant cost impacts) a full trial with sufficient duration was required to demonstrate these increases. Sufficient data would be required to give a statistically significant result that OWF developers, operators and owners/shareholders, and OEMs could have used in justifying applying these strategies across their portfolio.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

The proposed field tests would have reduced the uncertainty in the predictions of the economic benefits of WFC, lowering the risk of the technology, increasing its acceptance and TRL level.

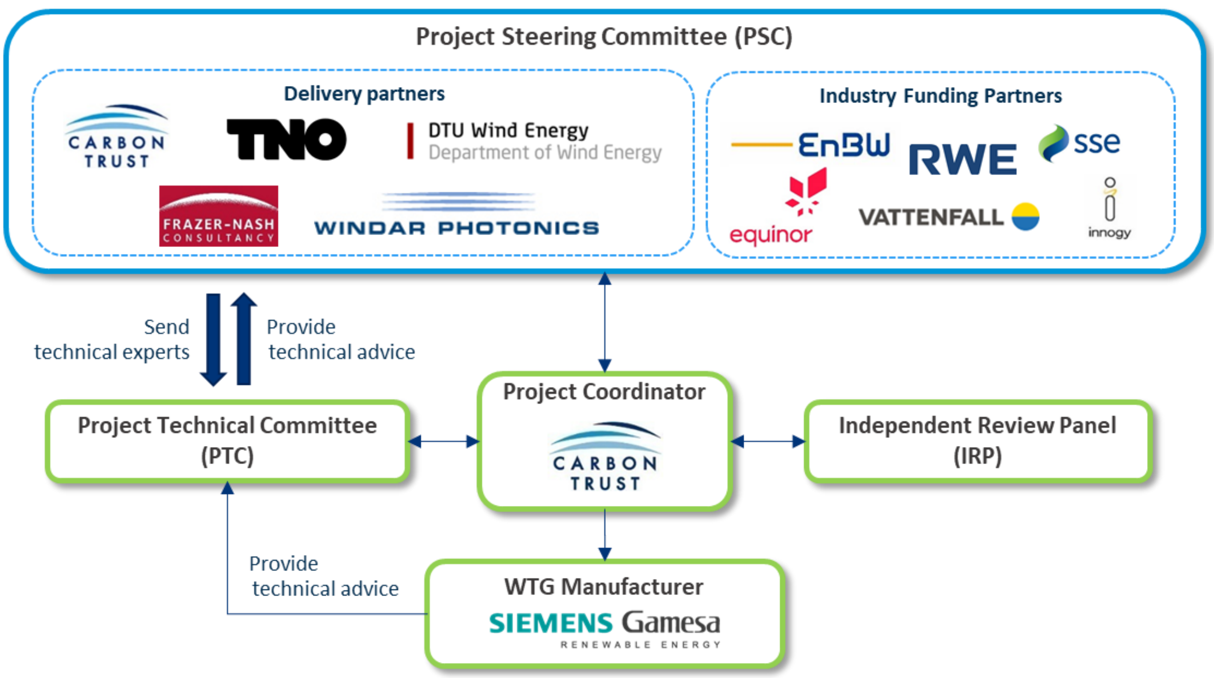
MOTIVATION OF THE PROJECT

Currently, offshore wind farms are not fully optimized to maximise the energy production of the wind farm as a whole, as each turbine is operated individually to maximize its own power production ('selfish turbine').
It is predicted that overall power production could be improved if wind turbines are operated in a coordinated way through Wind Farm Control (WFC) technologies. The yield increase on wind farm level will go along with a reduction in loads – thus reducing O&M costs.
In recent years, there have been significant advances in three research areas: wake flow modelling; data processing; and LiDAR technology. These developments, as well as further research of wind farm control strategies and their likely impacts, hold promise for effective implementation of WFC strategies – motivated the development of the WFCT project and attracted investment from both the public and private sector.

CONSORTIUM AND GOVERNANCE

The WFCT project received public sector funding from the UK (through BEIS) and Dutch government (RVO grant number TEHE116127) through the EU DEMOWIND programme. The public sector funding was supplemented by funding from key industry partners who in addition to the financial support played a role in shaping the direction of the project through the Project Steering Committee and the Project Technical Committee.
The WFCT project brought together twelve partners from six EU countries and is supported by seven major offshore wind developers. The governance structure of the WFCT project is shown in Figure 1.

Figure 1: WFCT Project Governance



The Project Steering Committee (PSC) was the main decision body consisting of management representatives of the project partners. The PSC tracks the progress and assesses risks and results.

The Project Technical Committee (PTC) consisted of technical experts of the project partners. The PTC reviewed project outcomes and gave advice to the PSC.

The Independent Review Panel (IRP) contained a number of highly skilled and respected experts in the field to provide an independent and impartial view on the project.

The project team was assembled to maximise the success of the project collecting experience in project management, data analysis, measurement equipment and WFC strategies.

- Carbon Trust acted as the project coordinator leveraging extensive project management experience from managing the Offshore Wind Accelerator (OWA) programme.
- Having conducted a series of studies on wind farm control technologies, Frazer-Nash led the data analysis and the design and installation of load measurements campaign
- Windar supplied 9 ‘WindEYE’ two-beam LiDARs to measure the wind speed upstream of the turbines.
- TNO hold important patents on wind farm control, largely covering the developments pursued in the project. TNO aimed to use their state-of-the art FarmFlow model to investigate flow conditions, wake interactions and loads.
- DTU have developed ground breaking LiDAR technology and made their state-of-the art wake models Fuga and PossPOW available.
- The industry partners provided technical expertise, financial support and supported in finding a suitable wind farm test site for the project.

GOALS OF THE PROJECT

The goals of the project were threefold:

Increase in energy yield and reduction in O&M costs
The computational models of wind farm controls predict a 0.5-3.5% increase in energy yield (AEP), load reductions of up to 50% for some wind turbine components, O&M cost reduction by up to 4% and lifetime extension of up to 3% in a conservative scenario.

Increased industry understanding of best practice
Increased understanding on how to optimize wind farm operation to maximize economic benefits

De-risking and reducing uncertainty
Reduced uncertainty, through field tests, in the predictions of the economic benefits of WFC, lowering the risk of the technology, increasing its acceptance and TRL level.

This project has received funding from the *European Union’s Horizon 2020 research and innovation programme* under grant agreement No 691732

PROJECT TERMINATION

Following the completion of the mathematical modelling of several candidate wind farms at which to conduct the trials, the Project Steering Committee decided that the project had to be terminated. The reason for project termination was that no existing offshore wind farm could be found being available for the project to conduct the trials within the time limits of the project schedule dictated by public funding governance. The reasons for the project not finding a wind farm are discussed and explored in Section 4 of this report.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

2 METHODOLOGY

PROJECT PLAN

The Project Plan included the delivery of 8 Work Packages; these are as described as follows:

Bringing together multiple partners to successfully deliver a carefully managed, innovative, low carbon technology programme of work (WP1)

- Using the complementary strengths of our transnational consortium of industry and research partners to successfully deliver and communicate this demonstration and validation programme of work.
- Using the project team's experience of running international collaborations, (including recent site monitoring and validation tests, as well as control system modelling) to put together a credible project approach based on proven successful project research and delivery.
- Combining industry and research knowledge across Europe and making the best use of public and private funding.

Apply existing modelling techniques to specific operational wind farm(s) to identify appropriate control strategies (based on existing control capabilities) to demonstrate real LCOE reduction for validation (WP2).

- An Offshore Wind Accelerator (OWA) modelling project demonstrated that changing turbine set points, which is possible on today's wind farms, could have an overall LCOE benefit. This project took the same approach and aimed to implement it at full scale to confirm the potential. Once proven in an operational setting, the concept was thought to be able to be rolled out to other operational wind farms without the need for further technology development, strengthening the competitiveness of the European offshore wind market.
- By basing our control strategies on existing control capabilities, this was expected to both accelerate the time to market and be a cost-effective and resource-efficient way of reducing LCOE for offshore wind, reducing the environmental footprint and energy payback time of both existing and future sites.

Install measurement systems for validation testing (WP3);

- We intended to carry out our validation and testing activities on a European offshore wind farm, strengthening the European industrial technology base, and contributing to creating growth and jobs in Europe.
- Measurement systems were to be sourced from European industrial partners, contributing to market growth in Europe.

Carry out control strategy test on operational wind farm (WP4);

- It was envisaged that the demonstration and validation project would accelerate innovation of low carbon technologies, taking the TRL level of the wind farm control techniques from TRL level 5/6 to TRL level 7/8, in line with DemoWind2 and Horizon 2020 aims.
- The project focused on overcoming barriers to adoption of wind farm control, delivering tangible, near-term benefits to the OWA European Partners by making intelligent use of existing control capabilities in time for Round 3 Final Investment Decisions.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

Decommission measurement systems (WP5);

- Our aim was to work closely with measurement system manufacturers throughout the project. By providing feedback on equipment performance both during the trial and at decommissioning, we would allow the manufacturers to build on lessons learnt, strengthening the competitiveness and growth of these European companies by identifying requirements for innovations that meet the needs of European and global offshore wind markets.

Analyse data to determine: impact / benefit of investigated strategies; predictive ability of modelling methods; and applicability of control strategies to a range of wind farm designs (WP6);

- The results of this analysis were to provide a clear and concise summary of the operational validation data obtained during this project. This would enhance dissemination, providing demonstration of the benefits of using alternative control strategies, and allowing wind farm developers to apply the techniques directly to their projects.

Identify Technical Lessons Learnt (WP7)

- These technical lessons learnt will help to bridge the gap between research and the market, providing practical application advice for wind farm developers, operators and owners, as well as for wind turbine manufacturers (OEMs) based on reliable operational data and research experience.

Disseminate results of validation (WP8)

- To maximise user / market uptake, we have included a comprehensive results dissemination work package. This will ensure that the benefits of using the validated control strategies are fully communicated.

PROJECT EXECUTION AND DEVELOPMENTS LEADING TO PROJECT TERMINATION

For reasons explained and explored thoroughly in Section 4 of this report the WFCT Project was terminated at a stage where WP2 was about to be concluded and WP3 had already been started heading for equipment installation allowing for start of testing at the beginning of the winter season 2019/2020. The essential reason for the project termination was, despite several attempts, the inability of the project partners to secure access to a site at which to test the WFC strategies. The remainder of this section describes the methodology of WP2 which related to the development of the suitable WFC strategies.

Active Wake Control (AWC) is an approach of operating wind farms in such a way as to maximize the overall wind farm power production and minimize the fatigue loads on the wind turbine components. This section describes the methodology followed within work package 2 “Detailed modelling and methodology”, dealing with the numerical analysis for the selected wind farms and the setup of the trials. These activities have been reported in detail in the following three deliverable reports:

- Deliverable 2.1 Wind farm modelling
- Deliverable 2.2 Simulation-based analysis of the benefits from optimized WFC concepts
- Deliverable 2.3 Test scenario description for validation tests

This project has received funding from the *European Union’s Horizon 2020 research and innovation programme* under grant agreement No 691732

The main achievements, reported in these deliverables, are summarized in the following three subsections, respectively.

CONTROL STRATEGIES AND WIND FARM MODELS

As part of the numerical analysis in WP2, the parameters of different AWC concepts are optimized, and their potential benefits are evaluated. There are two concepts to AWC, usually referred to as induction control and wake redirection (or wake steering).

Induction control involves reducing the axial induction of upstream wind turbines in order to increase the wind velocity in the wake. Ideally, this results in reduced power production upstream, and increased production downstream so that the total power production in a row of turbines increases. The axial induction can be affected by increasing the pitch angle, modifying the rotor speed (using torque control), or both. The pitch-based option is more widely accepted and considered as more effective, but the final implementation in the Demowind WFCT project was to be decided in agreement with Siemens Wind Power as the wind farm OEM and the test site provider.

The second concept, wake redirection, is based on operating upstream wind turbines with yaw misalignment in order to generate a transverse force on the air flow and divert the wake aside from downstream wind turbines. The yaw misalignment itself reduces the effective rotor area, decreasing the power production. However, the wind speed at the downwind turbines increases due to the wakes being moved aside, which causes an increase of the total power production of the wind farm.

To determine the optimal settings for the two AWC concepts that achieve the highest benefits with respect to a selected performance criterion, a model is required. Ideally, this model needs to:

- have high accuracy to minimize the risk of significant underperformance in the field
- be capable to predict the effects of the considered AWC concepts on the power production and loads
- have computational complexity that allows optimization and analysis for all wind directions and speeds in reasonable time
- allow to predict the effects of the different AWC concepts on fatigue and ultimate loads
- be able to perform dynamic simulations with wind resources that vary in time and space

To this end, the following wake models were used: FarmFlow (TNO) and PossPOW (DTU). After detailed description of the wake models used in the project, a high-level qualitative

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

comparison was performed providing insight into the capabilities of the different models for the purpose mentioned above. The models have been compared for a number of properties, such as fidelity, computational complexity, maturity and validation, ability to model different AWC concepts, ability to perform dynamic simulations with time-varying wind resource, and terrain complexity.

SITE MODELLING

Within WP2, detailed site modelling, simulation and analysis were performed. These are described in Deliverable 2.2. The purpose was to assess the potential benefits (in terms of AEP increase) and risks (in terms of impact on the structural loading) related to the application of AWC to the three potential test sites considered in the WFCT project: for reasons of confidentiality these shall be referred to as Wind Farm Site 1, 2 and 3.

Within the Demowind WFCT project, both the induction control and wake redirection control were applied. Initially, the numeric evaluation was conducted for Wind Farm Site 1 and 2. After it became clear that both would not be available for the trials, Wind Farm Site 3 was selected as new test site and the analysis was performed for it as well.

Project partner TNO performed Annual Energy Production (AEP) analysis for both induction control and wake redirection control using their wake model FarmFlow for all three wind farms. DTU focused on the induction control only, and considered only Wind Farm Site 1 and 2. DTU did not consider wake redirection because their wake model PossPOW cannot simulate the wake flow under yaw misalignment.

Besides AEP analysis, TNO has also performed detailed analysis of the impact of AWC on the fatigue and extreme loads, as well as on the yaw actuator duty, for all three sites. It was beneficial for these analyses that all three sites have the same wind turbine type.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

3 KEY DELIVERABLES

Table 1 shows the originally agreed Milestones and the associated deliverables for the WFCT project. Those marked in green were completed; those marked in orange were partially completed.

Milestone number	Milestone Name	Responsible Partner	Deliverable
M1.1	Consortium Agreement in place, kick-off meeting	The Carbon Trust	D1.1 and D1.2 Project kick-off documentation: Internal document containing the kick-off meeting minutes and presentations, a screen grab from the project website and the initial Risk Register
M1.2	Inaugural meeting of the Independent Review Panel (IRP)	The Carbon Trust	IRP kick-off meeting documentation: Internal document containing the meeting minutes and presentations
M1.3	Stakeholder start-up workshop	The Carbon Trust	Stakeholder start-up workshop documentation: External document containing the workshop protocol, presentations and attendees list
M2.1	Wind Farm Control (WFC) concepts' parameters optimized	TNO	D2.1 Wind Farm Modelling: Internal report describing the different wake modelling approaches used in WP2, and providing a qualitative comparison
M2.2	WFC algorithm ready for testing	TNO	D2.2 Simulation-based analysis of the benefits from optimized WFC concepts: Internal report detailing the selected performance as well as the results from the optimization of considered WFC concepts
			D2.3 Test scenario description for validation tests: Internal report describing the WFC concepts selected for field implementation and testing in WP3 and WP4, and the validation test scenarios
M3.1	All software and hardware installed and ready for use (control interface, 9 nacelle mounted LiDARs, 1 scanning LiDAR, 4 x 24 strain gauges)	Frazer-Nash Consultancy	D3.1 Wind turbine/wind farm control interface: Internal report describing the interaction between the wind farm controller and the turbine controllers in terms of interface and data exchange
			D3.2 Flow measurement devices: Internal report describing the available and newly installed measurement devices for wind speed and wind direction measurement of the free stream and in the turbines' wakes
			D3.3 Load measurement equipment: Internal report describing the installed loads measurement equipment, their location, calibration and accuracy

WFCT
This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

			D3.4 Data acquisition, synchronization and storage: Internal report describing available data acquisition systems
M4.1	All devices in ready state, and trial to begin	TNO	D4.1 Description of the 12-month measurement campaign: External report describing the operation of LiDAR systems and load measurement equipment during the trial, as well as the data format and processing
M4.2	End of measurement campaign and control testing. Handover of turbine level control back to operator.	Frazer-Nash Consultancy	D6.3 Test trials report: Internal report comprising 12 monthly rolling reports
M5.1	All devices which were to be removed, have been removed.	TNO	D5.1 Decommissioning process report: Brief Internal report describing decisions and actions within the decommissioning of the installed instruments
M6.1	Final reports discussing: • Impact / benefit of investigated strategies • Predictive ability of modelling methods • Applicability of strategies to a range of wind farm designs	The Carbon Trust	D6.1 Internal report containing a summary of required measurement data (based on test plan from modelling WP2)
			D6.2 Summary of available measurement data: Internal report containing a summary of available measurement data
			D6.4 Final analysis report: External report containing the detailed analysis of the results
M8.1	Lessons learned workshop	The Carbon Trust	D7.1 Technical lessons learned report: Brief external report describing the main technical lessons learned. Information gathered on the 'lessons learned workshop' (WP8) will be presented in an annex of the report
			D8.1 Lessons learned workshop documentation

Table 1: Originally Agreed Deliverables

Due to the termination of the project as agreed by the Project Steering Committee in December 2019, the deliverables associated with Milestones 6 – 12 will not be completed. However, in the year between March 2019 and March 2020 a great deal of work was conducted by the project. This additional work will be documented in this section.

COMPLETED DELIVERABLES

Throughout the project lifetime a number of reports were completed, these are summarised below.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

WIND FARM MODELLING (D2.1)

The purpose of this report was to describe the wake models used in the project and present a high-level qualitative comparison, providing insight into the capabilities of the different models for the purpose of optimization and analysis of AWC concepts.

The models were compared for a number of properties, such as fidelity, computational complexity, maturity and validation, ability to model different AWC concepts, ability to perform dynamic simulations with time-varying wind resource, and terrain complexity. Instead of choosing one tool for the optimization and analysis, it has been decided to be more efficient and fruitful to perform a cross-validation study, i.e. use each of the models to analyse the benefits of the AWC settings, optimized by each partner (TNO and DTU). This cross-validation study provided useful insight into the potential benefits of the different concepts, and will be used to select the concept(s) for field testing.

SIMULATION-BASED ANALYSIS OF THE BENEFITS FROM OPTIMIZED WFC CONCEPTS (D2.2)

AWC is an approach of operating wind farms in such a way as to maximize the overall wind farm power production and minimize the fatigue loads on the wind turbine components. It consists of two concepts: pitch-based AWC (called Heat&Flux, “HF”), and yaw-based AWC (called Controlling Wind, “CW”). This report describes the results from the feasibility study of applying AWC to the three wind farms that were considered as the test sites in the WFCT project. The goal of this study was to assess the potential benefits of applying AWC in terms of power production increase and load reduction for these wind farms.

The HF concept achieves increased power output by reducing the axial induction factor (i.e. increasing the "transparency") of the wind turbines at the windward side of the farm. This is achieved by pitching the blades of the wind turbines or, equivalently, by derating them. While these derated upstream turbines will produce less electricity, the wind velocity in their wakes increases, enabling the downstream turbines to increase their power production. This results in a net increase of power output of the farm. In addition, the loads are more evenly distributed over the turbines.

The CW approach to AWC consists of introducing yaw misalignment to the rotors of the upstream wind turbines with respect to the wind direction. As result, the wakes behind the yawed wind turbines are diverted away from the downwind wind turbines. The yaw misalignment itself reduces the effective rotor area, decreasing the power production. However, the wind speed at the downwind turbines increases due to the wakes being moved aside, which causes an increase of the total power production of the wind farm.

Within the Demowind WFCT project, both the HF and CW concepts were first applied in numeric calculations to the initially selected candidate wind farms. For reasons unrelated to the trials, both Windfarms 1 and 2 were no longer able to be used for the trials; therefore the project team underwent a process to identify a suitable site. Eventually a Windfarm 3 was identified as the most suitable candidate at which to conduct the WFCT. This required that further analysis was conducted on Windfarm 3 to calculate loads and potential AEP gain. Project partner TNO optimized both the pitch (HF) and yaw (CW) settings using their wake model FarmFlow for all three wind farms, while DTU has focused on the pitch optimization only (HF) for Wind Farms 1 and 2. only using their software PossPOW. DTU has not considered CW optimization because PossPOW cannot simulate the wake flow under yaw misalignment. Furthermore, TNO has performed a detailed analysis of the impact of AWC on the fatigue and extreme loads as well as on the yaw actuator duty for all three sites. It was beneficial for these analyses that all three sites have the same wind turbine type.

In summary, the results of the numerical analysis are as follows:

For Wind Farm 1:

- HF increases the AEP of the farm by 0.08% based on FarmFlow simulations. Simulations with PossPOW indicate a very similar potential power benefit, namely 0.04%.
- CW increases the yearly power production by 1.17% (based on FarmFlow)

For Wind Farm 2:

- HF increases the AEP of the farm by 0.05% based on FarmFlow simulations. Simulations with PossPOW indicate a very similar potential power benefit, namely 0.03%.
- CW increases the yearly power production by 1.11% (based on FarmFlow)

For Wind Farm 3:

- HF increases the AEP of the farm by 0.17% based on FarmFlow simulations.
- CW increases the yearly power production by 0.6% based on FarmFlow simulations. The reason for the lower relative gain compared to Wind Farm 1 is due to higher turbulence intensity at Wind Farm 3.

For all three considered wind farms:

- Both HF and CW have in general a positive effect on the fatigue loads on the wind turbines.
- There is a considerable margin between the site-specific fatigue loads and the turbine class 1A load level
- Ultimate loads are not affected by HF and CW.
- The yaw actuator duty cycle increases by about 50% on an yearly basis under CW due to the increased yawing needed to track the yaw misalignment setpoints

TEST SCENARIO DESCRIPTION FOR VALIDATION TESTS (D2.3)

The report described scenarios for implementation and testing of the active wake control (AWC) concepts wake redirection (by yaw misalignment) and induction control (by pitch angle offset). More specifically, the following aspects are discussed:

- Test site layout: the layout of the wind farm selected for testing, and the wind conditions
- Test setup: how is the test campaign is organized in terms of phases as a risk mitigation measure, and which rows of turbines will operate in control mode in each phase
- Measurement equipment: what measurement equipment will be installed and where
- Test matrix for wake redirection control and induction control: table(s) containing the yaw misalignment settings and the pitch angle offsets for each control turbine

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

- Duration of trial and data acquisition: how long will the measurement campaign last and which signals will be logged
- Number of data points: what is the expected number of 10-min data points useful for quantification of the benefits from AWC

FURTHER WORK UNDERTAKEN

Two pieces of work that were completed prior to project termination was the development and procurement of the load measurement systems by Frazer-Nash and the Technical Due Diligence Report compiled by Innogy – both of these reports are described below:

LOAD MEASUREMENT INSTRUMENTATION

In the following section, an overview of the tower loads system is presented. A summary of progress made to date in delivering the system in support of WFCT is also presented.

Instrumentation Purpose
The original intent of the system was to measure tower strains on four towers using strain gauges, and from this data infer thrust in order to capture validation data for modelling. By increasing the confidence in the modelling, we would be a step closer to building an established modelling tool chain that can be used to predict the benefits of WFC to other sites. It should be noted that the estimation of thrust on the rotor from strain gauge measurements is a development topic in itself.

The original plan was to achieve acceptance of the predicted impact that WFC has on loads through modelling, but the test site wanted more confidence that the loads are not going to detrimentally impact the turbines as a result of running this trial. TNO and Innogy developed a staged approach for running the trial to help manage the risks associated with implementing WFC at the site.

A secondary objective of the loads system, therefore, was to monitor the tower loads so they could be compared with those modelled to validate the predictions during the "soft start" to the trial. Frazer-Nash could then report the loads measured, and how they compare with those modelled. This data would then be used to inform decisions by key stakeholders as to whether or not such loads are acceptable to site, and hence progress with the trial. It is understood that there was no requirement to configure the system such that it can be reviewed in real time, and hence would not be serving a safety critical function.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

Summary of Timeline

Following a period of engagement, including the completion of a range of technical due diligence activities, shareholders of Wind Farm 3 gave in February 2019 their provisional agreement to host the WFCT test trails.

WFCT was due to commence in January 2020, with installation of the various instrumentation systems due to take place during the fourth quarter of 2019. Trials planning and preparation works, therefore, needed to take place between February and September 2019. To this end, Frazer-Nash worked on the design and assembly of the strain gauge instrumentation systems, and supporting other project activities between February and September 2019. Work on the systems was halted in September 2019 when the test site advised that it was unable to proceed with hosting WFCT.

Summary of Progress

Summary of progress against the objective of delivering and installing loads instrumentation can be broadly categorised in the following areas:

Detailed Hardware Design

Having developed the high-level hardware architecture at the project outset, a detailed design and specification was completed. The detailed design included, but was not limited to: suitable locations to install the instrumentation, specific components (and identification of suppliers) for the instrumentation systems, and appropriate packaging for the hardware, being cognisant of spatial and thermal constraints.

Hardware Build

Frazer-Nash completed the majority of inspection, preparation and assembly activities relating to the hardware of the instrumentation systems. A selection of images from one of the systems under build is shown in the following figure.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

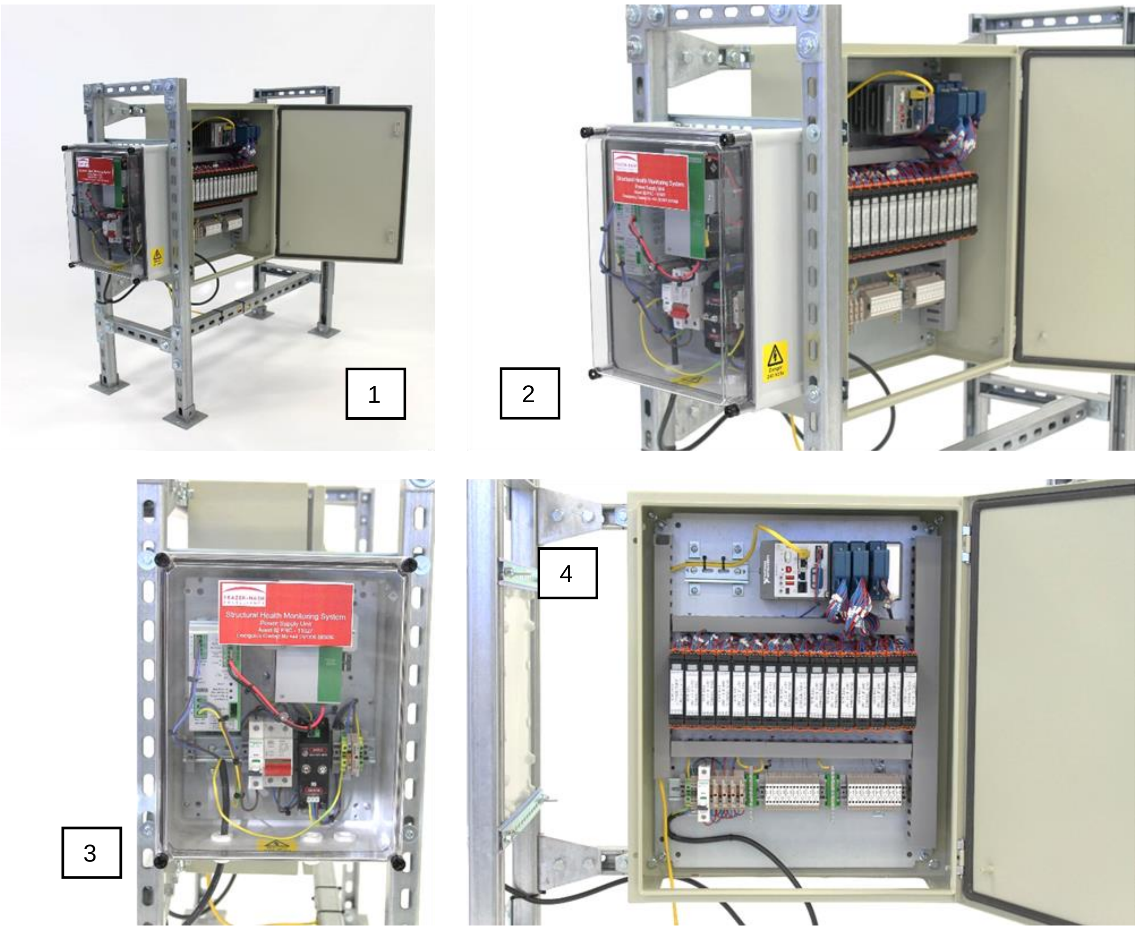


Figure 2: Images of one of the load instrumentation systems: 1) assembled unit and supporting frame, showing power supply and DAU (door open); 2) close-up of assembled unit, showing power supply and DAU (door open); 3) close-up of power supply; 4) close-up of DAU

Software Development

Frazer-Nash developed bespoke algorithms to control the data acquisition system, and record and analyse the strain data captured by the hardware. This was largely implemented on one of the data acquisition units.

Documentation

Progress against the above items was detailed in a range of draft documentation, outlined below:

- Risk Assessment and Method Statement. This document outlines the activities that would have been completed on site to enable installation of the loads instrumentation systems. Such a document would have been mandatory to enable installation works to be completed.
- Factory Acceptance Test Plan. This document describes the tests that would have been completed on finished instrumentation systems (software and hardware) prior to their shipping to site for installation. Undertaking such tests ensures high build quality, de-risking the installation works that would have taken place in the future.
- Site Acceptance Test Plan. This document describes the tests that would have been completed on the instrumentation systems once they were installed, prior to leaving

WFCT
This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

site. Completing such tests are essential to ensure correct installation of instrumentation, de-risking future remote operation of equipment.
- System and Software Specification. This document summarises the loads measurement system architecture and, at a high level, describes the functionality of the software used to drive the system.
- Detailed Software Specification. This document outlines the detailed implementation of the derived algorithms and associated logic in the software used to drive the loads measurement system.

TECHNICAL DUE DILIGENCE REPORT FOR WIND FARM 3

Before committing to hosting a WFC demonstration the test site owners identified a number of risk-based topics which needed to be assessed prior to approving a trial start-up. The test site owners highlighted that overall asset integrity was of highest importance for informing a final decision to approve control trials and needed to be credibly proven through technical due diligence (TDD). In addition to requesting that comprehensive TDD must result in no or low technical asset integrity risks the TDD also had to address the following topics:

- Impact of WFCT on foundation loads and possible lifetime reductions
- Interplay and possible adverse effects of WFCT with other wind turbine software upgrades
- Evaluation of anticipated higher O&M costs and increased failure rates for related components
- Review of costs analysis in regards to the demobilization of test equipment, notably blade sensors etc. in case of trial stop

Summary findings of TDD risk-based assessment were as follows:

- All identified risks were seen to be acceptable (i.e. NO or LOW asset integrity risks).
- Overall conclusions pointed towards WFCT having zero or positive impacts on the wind turbine and substructure loading and asset lifetime.
- Sufficient safeguards (i.e. the test ramp up proposal) were built into the test set-up to ensure that any unforeseen risks could be identified and effectively mitigated.
- Model predictions could be verified during the trial by periodic load assessment using data from the test measurement equipment.
- Costs of test equipment in case of trial stop were considered to be acceptable.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

4 LESSONS LEARNED AND CONCLUSIONS

PROJECT TERMINATION

During the project lifetime a number of difficulties were encountered in identifying a suitable site at which to conduct the trials. For reasons unrelated to the WFCT project the owners of Wind Farms 1 and 2 decided that they were unable to offer their site for the trials which led to a search for an alternative site.
Eventually Wind Farm 3 was identified; however, following a year of analysis, negotiation and planning the site management at Wind Farm 3 decided not to go ahead with the trials. This decision left the project partners with no alternative but to terminate the project.

LESSONS LEARNED

The following list encapsulates some of the conclusions and lessons learned from the WFCT project

Where possible; ensure the status of wind farms at the contracting phase
During the inception of the WFCT there was still uncertainty as to the location at which the trials would be conducted. For future similar projects it would be beneficial to know with more certainty which site would be used during the project. That said; given the developments in this project – such mitigation would not have helped given that Wind Farm 1 withdrew from the project for reasons unrelated to the WFCT project. Despite all efforts and careful planning, the obstacles could only be identified during the project and the final decisions of wind farm owners could not be foreseen at project start.

From a project planning perspective, it would be ideal to ensure buy-in from a test site as one of the first milestones before investing in equipment and conducting much technical work. However; the caveat to this is that the technical work may be necessary to convince the site that the project is interesting and valuable.

Get assurances from sites that they are committed to the project
The ownership of wind farms is such that those operating the wind farm are rarely the same departments as those involved in the central R&D activities. Different parts of the same organisation have very different sets of objectives. Identifying these different objectives and satisfying the needs of all stakeholders is essential. The asset managers are often risk-averse as they want to maximise the yield/profit for the owners or shareholders. In addition, the asset managers are typically not involved in R&D activities.

Ensure that all stakeholders are engaged from the outset

- the turbine manufacturer needs to be involved in relation to modelling and planning of the test campaign
- turbine manufacturer to provide guarantees regarding assets when used in non-standard ways
- the site owner needs to procure the installation/decommissioning of the equipment to be installed (for insurance reasons);

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732

- the equipment installation needs to comply with existing service agreements;
- the wind turbine manufacturer, the site-specific service provider and the site owner's O&M team all need to be involved in the roll-out of novel WFC strategies
- the wind turbine manufacturer should ideally be contracted as a full project partner – rather than in an advisory role.

Obtaining visibility of other developments in the sector
Towards the end of the project it become apparent that a turbine manufacturer was developing a product that would rival the WFCT strategies being developed. This product shows that WFC strategies are a key area of research and actually of great interest to the offshore wind sector. It transpired that the rival product was far closer to commercialization than previously. Wind Farm 3 cited this closeness to commercialization as another reason that they did not wish to take on the perceived risks of the WFCT project.

Although the majority of consortium members were not aware that the turbine manufacturer was developing a commercial product from the beginning of the project as there was no information regarding the development of the product in the public domain; it was known that they were developing their internal IP with regard to WFC technology. Due to the confidential nature of the research, the project consortium had no visibility of the parallel development. It transpires that a commercial product that is offered by the turbine manufacturer (who can give guaranties and warranties) has a greater attractiveness than a R&D prototype set of control strategies that comes without guarantees and warranties.

Address all legal obstacles as soon as feasible
One of the major obstacles to the continuation of the WFCT were legal matters; specifically, there were conflicts identified between two key contracts.
The WFCT project required the turbines to operate in a non-standard way and Wind Farm 3 was specifically selected because we were informed that the turbines to be used in the trial were out of warranty. However, a new Service and Warranty Agreement (SWA) had been agreed between the owners of Wind Farm 3 and SGRE – the manufacturer of the turbines at that site. Ultimately one of the major reasons for project termination was that there were unavoidable conflicts between these two contracts. Unfortunately, because the negotiations regarding the contract were confidential, the project partners had no visibility of the SWA.
In terms of lessons learned – one of the reasons that Wind Farm 3 was selected was due to being informed that the turbines were out of warranty; the presence of the newly negotiated SWA agreement changed that picture. The project partners were not informed of the contract being negotiated. A lesson to learned here is to ensure that where possible legal issues such as this one is identified as early as possible.

Load impacts (technical due diligence)
In order to convince the shareholders of Wind Farm 3 of the benefits and risks of conducting the WFCT at their site the project partners created a Technical Due Diligence Document. This is a valuable piece of work which addresses the loads and risks of these loads on the turbines.

Gradual roll out as risk mitigation strategy
One of the risks identified in the project was that starting to implement to the WFC strategies would have unknown consequences on the turbines. This was clearly not acceptable for those whose concern was the protection of the assets. In order to mitigate this risk a 'soft start' strategy was developed. In this strategy, the WFC methods would be ramped up over a month-long period in the existing wind farm whilst loads on the turbines would be measured. Only after this period the full pitch and yaw WFC strategies would be applied in full when the risk to the turbines had been shown to be acceptable.

Follow-on activities
The knowledge gained in conducting this project will be of value to the project team when considering the uptake of WFC in the future. SGRE WFC product which is close to market will require validation and pilot project is currently being undertaken. We are investigating ways in which the knowledge gained in the WFCT project could be combined with the SGRE project to create knowledge for the offshore wind farm sector and to help de-risk and gain acceptance of WFC strategies.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 691732