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Project Acronym: TotalControl

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Project final report

Deliverable D6.5

HISTORY OF CHANGES		
VERSION	PUBLICATION DATE	CHANGE
1.0	11.08.2022	Initial version

Contents

1. Introduction

The TotalControl project was originally planned to be running during the period 01-01-2018 to 31-12-2021. However, primary due to the effect of the C-19 pandemic on the scheduled full-scale experiments, the project period was extended with 5 months, which meant that the project was successfully concluded 31-05-2022.

Overall, TotalControl is organized in 4 scientific work packages (WPs) dealing with respectively 1) a 'test bench' package (i.e. a 'collection' wind farm flow field models of various fidelities); 2) open-loop wind power plant (WPP) control; 3) enhanced wind turbine (WT) control functionalities supporting WPP control; and 4) closed-loop WPP control. In the formulation of the project, it was found vitally important to validate developed models against experiments — preferably full-scale experiments where possible — to ensure confidence and thereby direct use of the achieved results to the benefit of the wind energy community. Consequently, all scientific WPs contain both modelling and follow-up experimental validation, and the main achievements of each of these will be described in the following. In addition to the four scientific WPs, TotalControl comprises a management WP as well as a dissemination WP. The dissemination activities, given in terms of project related conference participation and journal paper output, are also described in the following.

The project structure is illustrated in Figure 1 below.

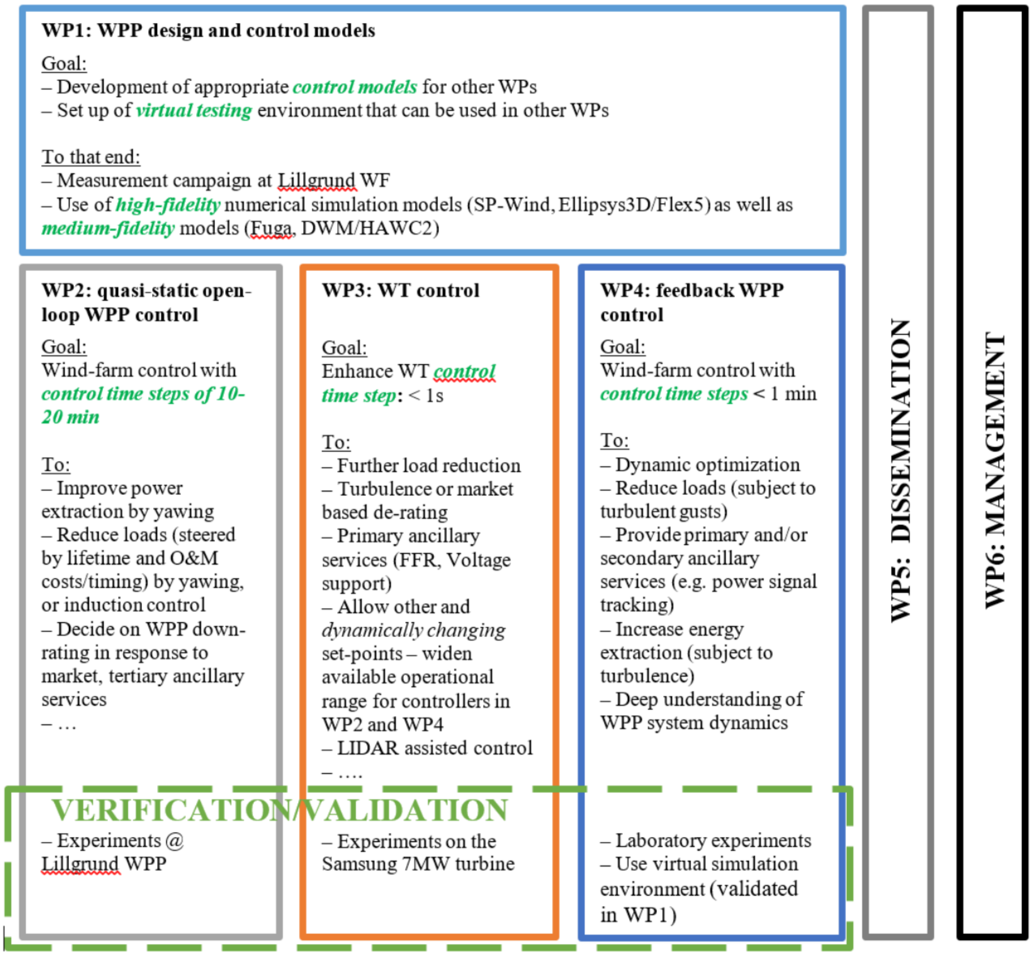

Figure 1: Schematic overview of the project structure.

2. WP1 - WPP design and control models

2.1 A short introduction to the overall aim of WP1

The main objective of WP1 is the development and validation of WPP design and control models. This includes models of different complexity – fast simplified models for online WPP control and high-fidelity models for virtual testing and design of WPP controllers. The work package has been organized in three main tasks, related respectively to the generation of validation data for model development, the set-up and validation of high-fidelity simulation tools for wind farm flow and electromechanical simulations and the development and initial verification and validation of fast control models.

The main objective of **Task 1.1** is set-up of an extensive wind-farm measurement database based on a new measurement campaign in the Lillgrund wind farm. The measurements include lidar measurements with 3 lidars as well as synchronized SCADA data, and load measurements. The task has formally one subtask, which encompasses all the work of Task 1.1, i.e. Task 1.1.1: Measurement campaign at Lillgrund wind farm.

The main objective of **Task 1.2** is the set-up and validation of high-fidelity simulation tools for wind farm flow and electromechanical simulations, which can be used as a virtual testing environment for further controller development and testing of research hypotheses in other WPs. Next to that, a reference database is also set-up with high-dimensional flow datasets, which can be used for testing and calibration of simpler wind farm models. Following subtasks were included

- Task 1.2.1 was focusing on validation of different high-fidelity wind-farm models against Lillgrund wind farm data
- Task 1.2.2 was concerned with the definition of a reference wind farm and power grid, for use in generation of reference data sets and later testing of control models (in WP2 and WP4)
- Task 1.2.3 was concerned with the generation of flow data for the reference wind farm and the Lillgrund wind farm
- Task 1.2.4 focussed on the set-up of a detailed electro-mechanical analysis environment for wind power plants
- Task 1.2.5 was aiming at the upgrade of the existing Dynamic Wake Meandering Model (DWM), a mid-fidelity model, for non-neutral ABL conditions and turbine yaw control

Finally, the main goal of **Task 1.3** is the development and initial verification and validation of fast control models, that are sufficiently fast to use for online control in WP2–4. Data and models from Tasks 1.1 and 1.2 are used as reference, as well prior data available to the consortium. In four subtasks, models are developed and evaluated, that roughly have the same goal (in terms of describing the wind-farm flow field), but are based on different simplifying assumptions:

- Task 1.3.1 was concerned with an upgrade of Fuga, a fast wind farm model based on linearized Navier–Stokes equations, for yawed rotors (allowing wake steering as control approach) and strongly stable stratification
- Task 1.3.2 was developing and testing the coupling of a Gaussian wake merging method to a background ABL model to parametrize cumulative farm effects
- Task 1.3.3 testing and validating a simple dynamic wind farm model, ie. the inhouse LongSim model developed by DNV
- Task 1.3.4 Exploring the potential of machine learning approaches to wind farm control

2.2 A short description of the deliverables carried out in WP1

The following deliverable describes the achievements of Task 1.1:

- D1.1 provides the measurement dataset of the TotalControl Lillgrund offshore measurement campaign carried out between September 2019 and February 2020. Three long-range DTU WindScanners (i.e. pulsed scanning Doppler wind LiDARs) were installed on Lillgrund wind turbine transition pieces and used to measure the flow field both upstream and within the farm. SCADA data of all turbines, resampled at a 0,5Hz frequency is also available. Moreover five turbines in the farm were equipped with load sensors; this data is available starting from November 2019 at 10Hz sampling frequency.

The achievements of Task 1.2 are described in 6 deliverables:

- D1.2 details the validation of high-fidelity large-eddy simulations with the Lillgrund measurement date from D1.1. It is probably the first full-scale validation of an LES model that includes aeroelastic turbine representations against Lidar, SCADA and load measurements in a wind farm. Two different LES models are validated and compared (SP-Wind, KU Leuven; and Ellipsys3D, DTU). In addition, the DWM model is also compared to measured wake profiles.
- D1.3 introduces, next to Lillgrund, a modern-sized wind farm that is used/compared as a reference throughout the project in all possible simulation tools, and that can be shared fully open source with the scientific community. The reference farm includes a layout that is amenable to high-performance flow simulations, a power-grid layout, and the selection of a reference turbine (i.e. the DTU10 MW turbine)
- D1.4 provides highly detailed virtual reference data (flow and loads) for further testing and comparison of (fast) control models and controllers. Data are based on the Reference Wind Power Plant layouts, and are made available open source to the scientific community through the Zenodo platform. Part A (D1.4a) provides detailed inflow data for different atmospheric conditions, based on precursor simulations (see https://zenodo.org/communities/totalcontrolflowdatabase/), whereas Part B (D1.4b) provides the wind-farm flow and load data (see https://zenodo.org/communities/totalcontrolwindfarmdatabase/).

- D1.5 provides an electro-mechanical model of the reference wind power plant. Both a high-fidelity electrical model and a fast control model for the electrical side are presented, complementary to the high-fidelity flow models used in Tasks 1.2.1 and 1.2.3.
- D1.6 reports on a major upgrade of the DWM model, allowing for non-neutral stratification and turbine yaw. DWM is a mid-fidelity model that is much faster than the high-fidelity models (based on large-eddy simulations) used in Tasks 1.2.1 and 1.2.3, but too slow to use directly as a fast control model. It allows for more extensive parameter studies prior to LES or field testing in WP2–WP4.

The achievements of Task 1.3 are described in 4 deliverables:

- D1.7 reports on the upgrade of Fuga, so that wind-farm wakes can now be represented both in the presence of different stratification regimes and in the presence of yaw. The model has been used in WP2 for optimization of wind-farm set-points etc.
- D1.8 reports on the formulation and validation of a coupled model consisting of a Gaussian wake-merging model, and an atmospheric perturbation model that allows to parametrize gravity waves. Results from D1.4 were used as reference
- D1.9 reports on the validation of DNVs LongSim simulation tool versus historical Lillgrund SCADA data, in combination with data from the nearby Drogden lighthouse for classification of stability conditions. The validated model is further used in WP2–WP4
- D1.10 explores the potential of machine learning as an alternative to first-principles modelling. The TotalControl modelling approach strongly relied on first-principles modelling, which we believe to be the most appropriate for wind-farm control applications. Nevertheless, with this task and deliverable we wanted to avoid missing important evolutions in machine learning that might require us the rethink our main paradigm. The conclusion of the deliverable was that this was not necessary for the time being.

2.3 An overall conclusion of the impact of the WP1 work

Taks 1.1 has provided a unique new dataset on an offshore windfarm that combines SCADA data with measurements form three long-range scanning lidars, allowing for inflow characterization, as well as a detail of some wind-turbine wakes in the farm. In addition, load sensors were also installed on five turbines, with data available for the last 4 months of the campaign. These data have been used in Task 1.2 for validation of wind-farm large-eddy simulations (LES) that were coupled to aeroelastic turbine models, and both power and load predictions were compare to measurements.

Next to validation of LES models, Task 1.2 has developed a reference wind-farm, and virtual flow datasets for this wind-farm that have been used throughout the project, and are available open source to the community. Meanwhile, these datasets have also been used by other projects, such as the EU FarmConners project.

Task 1.3 has developed, verified, and validated fast control models that have been extensivelly used for the development of effective control algorithms in WP2–WP4. These models include Fuga, LongSim, and the Gaussian wake merging model.

3. WP2 - Quasi-steady open-loop WPP control

3.1 A short introduction to the overall aim of WP2

WP2 of the TotalControl project deals with various aspects of *open-loop* quasi-static control of WPPs. The goal of the activity is to develop and validate optimized WPP control schemes, for which the optimal economic WPP performance — including both power, load and electrical aspects — is pursued over the WPP lifetime. The resulting optimized control schemes are conditioned on plant layout as well as on grid supervisory commands and electricity prices on time scales of the order of 10 minutes.

The work package has been organized in five main tasks, related respectively to cost modelling (Task 2.1); optimization of WPP set-points (Task 2.2); optimization of reactive power dispatch (Task 2.3); assessment of variations in annual reliability levels for main structural components when applying the derived WPP control schemes (Task 2.4); and full-scale validation of optimized control schemes (Task 2.5). Most of these main tasks have been defined and specified activity wise in sub-tasks as follows:

Task 2.1 encompasses:

- A statistical analysis of the effect of fatigue loading on O&M (Task 2.1.1), which quantifies the variation in the annual reliability levels and the effect of fatigue on operation and maintenance costs. Relevant correlations have been investigated using an existing database of costs, failures and SCADA data;
- Cost of fatigue degradation and O&M of WPP WT *mechanical* components (Task 2.1.2). Costs of fatigue degradation are accounted for by associating this cost with the accumulated fatigue life consumption of relevant main components of the individual WPP WT's in an aggregated manner, whereas cost of O&M is quantified using a probabilistic approach;
- Cost of fatigue degradation and O&M of WPP *electrical* components (Task 2.1.3). In the context of TC the main emphasis is on aspects related to power converters, where the impact of different control strategy alternatives to the lifetime of power electronics is investigated;
- SCADA-based conditions monitoring and fatigue estimation (Task 2.1.4), in which the potential of conventional 10-minute SCADA data for condition monitoring is exploited with the aim of measuring the health of components and to predict impending failures.

Task 2.2 encompasses:

- Aspects of ancillary services (Task 2.2.1), where the ability to track and respond on reference signals provided by the grid operator are investigated;
- WPP set-point optimization using a *medium* fidelity approach (Task 2.2.2). In this task both power and load aspects are taken into account, which is facilitated using the state-of-the-art aeroekastic model HAWC2 in combination with a DWM approach to model the complicated un-steady WPP wake affected flow field;
- WPP set-point optimization using a *low* fidelity approach (Task 2.2.3). Three different model platforms are used in this study: LongSim (a simplified engineering wake model

based on the DWM philosophy combined with a load surrogate model), Fuga (a linearized CFD solver) and coupled Gaussian model with linear merging;

- A study on the sensitivity set-points to WT loads and WPP model accuracy (Task 2.2.4) is performed based on the results emerging from Task 2.2.2 and Task 2.2.3;
- Estimation of multi-dimensional rotor performance data for set-point optimization (Task 2.2.5).

Task 2.3 deals with optimization of reactive power dispatch, and the goal is to develop a wind power plant control algorithm, which optimizes the reactive power dispatch between the WPP WTs, so that the total losses are minimized. The strategy for the optimal control is to utilize the possibility of diverse set-points of the different wind turbines, and thus minimize the total power losses within the WPP.

Task 2.4 deals assessment of variation in the annual reliability levels of structural components when applying the derived WPP control schemes. For WPPs the variations in the wind farm conditions and different power requirements can lead to faster structural degradation than anticipated in the standard design approach. Thus, in this task the variation in the annual reliability levels of WT structural components ─ when applying different WPP control schemes developed in the project using specific probabilistic models that govern the fatigue design loads and failure conditions ─ is quantified;

Task 2.5 is about full-scale validation of optimized quasi-steady control schemes using the Lillgrund WPP as the demonstration case. Originally, the plan was to use two WTs for this study, but during the course of this task it became, quite extraordinary, possible to base this study on optimal control of an entire row of WTs (i.e. row A).

3.2 A short description of the deliverables carried out in WP2

The following successfully concluded deliverables describe the achievements of the WP2 tasks:

D2.1 — covering the outcome of Task 2.1.1, Task 2.1.2 and Task 2.2.3 — has presented a cost model that quantifies representative costs of operations and maintenance (O&M) due to fatigue degradation of mechanical and electrical components. This is a trade-off between energy capture and maintenance costs. The impact on annual energy production (AEP), failure costs and lifetime is presented. This deliverable gives a fast method for estimating the impact of fatigue on O&M costs.

D2.2 accounts for the outcome of Task 2.1.4 and provides an overview of techniques to measure the condition of a wind turbine, comparison of the main approaches to monitoring integrity, including turbine alarms, Condition Monitoring Systems (CMS), SCADA-based condition monitoring (SCM), inspections along with the main approaches to measuring life. Examples showing the potential of predictive maintenance in reducing O&M costs and overall LCoE, through a reduction of both the downtime associated with failures and the cost of the necessary repairs, are given.

D2.3 accounts for the work performed in Task 2.2, and quantifies the benefit to WPP production and fatigue damage reduction to major wind turbine structures through the use of selective wind turbine de-rating and yaw control strategies. These wind farm supervisory control strategies are modelled using diverse software packages, which possess various wake models of different fidelities. Effects of such WPP control strategies on the power production and loads reduction in the Lillgrund wind farm are compared using three low fidelity wake model approaches (LongSim, Fuga and Gaussian Wake) and one medium fidelity wake model approach (DWM). The de-rating of wind turbines is implemented selectively keeping several objectives such as maximizing power or maintaining a certain power level, while minimizing loads. The yaw control is implemented to maximize power production separately uncoupled to de-rating.

D2.4 refers to Task 2.3 and describes a wind farm reactive power control algorithm to optimize the reactive power dispatch between the wind turbines in a farm, so that the total electrical losses are minimized. The studies were validated at the Lillgrund wind farm using real measurements for 1 year. It has been observed that electrical losses can amount up to 1% of the annual energy production. The developed optimization methodology can reduce the energy losses substantially by around 6% of the total energy lost.

D2.5 refers to part of the work performed in Task 2.4 and demonstrates the benefit of de-rating selected rows of wind turbine in Lillgrund. Damage equivalent load and energy production maps over the Lillgrund wind farm for different wind conditions, using a fast surrogate model that sufficiently captures the wind farm wake flow, were made. The results showed the net AEP increase of the wind farm with de-rating was about 2%, and with an estimated 5-years increase in lifetime a net AEP increase of 4% was quantified, which resulted in an LCOE reduction of 3%.

D2.6 complements D2.5 in reporting the outcome of work carried out in Tasks 2.4. The report deals with and assesses the possibility for reduction of OPEX based on maintaining target reliability levels through control. The framework described within D2.6 consists of three main elements: 1) Quantifying the sensitivity of the wind turbine loads with respect to environmental conditions, including wake effects, for any turbine in the wind farm; 2) Establishing the site-specific loading history (or projection) using a combination of on-site measurements of environmental conditions and loads and simulations to complement the measurements; and 3) A procedure to compute the annual reliability index based on the information available in 1) and 2).

D2.7 covers work done in Task 2.5 regarding full-scale validation of an optimal *axial induction* controller designed for an entire row of WTs – i.e. row A consisting of 7 WTs – of the Lillgrund WPP. The optimal controller was designed using steady-state optimizations in the LongSim and Fuga codes, which predicted a small but significant power gain along with a considerable reduction in fatigue loading. Based on analysis of 3 months of data, the measurement are showing initially very promising results, although considerably more data still needs to be collected before robust conclusions can be drawn. It is therefore decided to continue the field test beyond the TotalControl project, and furthermore, once more data has been collected and analysed, it is considered to test a similar, but dynamic, controller for the whole wind farm, where the set-points will change with wind direction.

3.3 An overall conclusion of the impact of the WP2 work

Task 2.1 has developed cost models needed for deriving optimal WT set-points. More specifically, these cost models, applied together with various controllers, can facilitate reduction turbine loading and thus in turn leading to reduced maintenance costs.

Task 2.2 deals with 'design' of set-points, which reflects the optimal balance between WPP power production and cost of WPP loading as seen from an economic perspective (i.e. minimization of COE), and have quantified the benefit to WPP production and fatigue damage reduction to major wind turbine structures through the use of selective wind turbine de-rating and yaw control strategies. In addition, the sensitivity of the optimal set-point distribution on the model fidelity has be investigated by comparing the optimal set-point distribution over the WPP resulting from simplified steady-state models and the detailed unsteady formulation, respectively. Using AEP as the metric, the result is that the overall gain is of the same order of magnitude for both categories of models (i.e. of the order 1%).

Task 2.3 has developed a wind power plant control algorithm, which optimizes the reactive power dispatch between the wind turbines, so that the total electrical losses, usually of the order of 2-3% of the total energy production, are minimized. The developed optimization methodology can reduce the energy losses substantially – i.e. around 6% of the total energy lost. Sensitivity studies show that while increasing the converter size does not have any impact on reducing losses, increasing the OLTC voltage settings can double the energy saving.

Task 2.4 deals with quantification of the variation in the annual reliability levels of structural components when applying different WPP control schemes developed in the project. This is accomplished developing an innovative probabilistic model, which govern the fatigue design loads as well as failure conditions. A demonstration study has been set up, in which the new method uses both the results of aeroelastic simulations and direct load measurements on a Lillgrund WT to determine the annual expected fatigue damage equivalent moment at the blade root. Further, a neural network was developed to quantify the inflow turbulence with wake effects included as based on the measured 10-minute SCADA statistics of the wind turbine. The output of the neural network demonstrated a potential for reduced scatter in the turbulence measured using the nacelle anemometer. The neural network can feed into the turbine control system, whereby – if it detects that the inflow turbulence is higher than a set allowed limit – the turbine can be de-rated, or the upstream turbine can be de-rated to lower the mechanical loads.

Task 2.5 deals with full-scale validation of optimized quasi-steady control schemes using the Lillgrund WPP as the demonstration case. The original scope, based on only two de-rated WTs, was during the course of the project extended to include an entire row of seven de-rated WTs. Based on analysis of 3 months of SCADA data from the seven WTs, the measurement are initially showing very promising results, although more data still needs to be collected before robust conclusions can be drawn. The campaign is therefore ongoing beyond TotalControl project, until satisfactory statistical significance has been achieved.

4. WP3 - Enhanced WT control

4.1 A short introduction to the overall aim of WP3

Work Package 3 of the TotalControl project was concerned with developing and testing adaptations of the wind turbine controller, which could be beneficial in the context of wind farm control.

In Task 3.1, various controller adaptations were developed, and tested in simulations, while in Task 3.2, controller adaptations were implemented and tested on a real turbine in the field, namely the 7MW Levenmouth Demonstration Turbine (LDT) just off the coast of Eastern Scotland.

Task 3.1 was concerned with a number of different turbine controller features and adaptations covering a variety of techniques with different goals, ranging from increased operational flexibility to optimising benefits in varying physical and market conditions, through to more advanced controller architectures and design methods aiming to reduce loads and hence capital cost. Where possible, a model of the Samsung 7MW turbine was used as a common baseline for these developments, so that they could be adapted specifically to this turbine in preparation for field testing in Task 3.2. The particular features investigated in Task 3.1 are summarised as follows:

- Active power control: although the power produced by the wind turbine is fundamentally determined by the wind speed incident on the rotor at any time, the controller is able to provide some flexibility in the power production, where this can help with three specific goals:
    a) Active wake control: modifying the power production affects the turbine wake. Wind farms see very significant losses due to wake interactions between turbines, so the control of the individual turbines in a wind farm can be modified in order to optimise the performance of the wind farm as a whole rather than each turbine individually. This includes maximising total power, as well as reducing fatigue loading to extend plant lifetimes.
    b) There are always trade-offs between power production, which generates immediate revenue, and turbine loading, which affects O&M costs and plant lifetime in the longer term. This is an economic trade-off, which can vary in time depending on the current power price.
    c) Power can be varied in response to demands from the grid system: at different times, the grid may demand a curtailment of wind farm power output, or it might be willing to pay for additional flexibility, for example by keeping a margin of power in reserve, or responding dynamically to changing grid frequency. These capabilities are referred to as providing ancillary services for the grid.
- Load reduction: although power can be traded against loads, loads can also be reduced without compromising power production by making use of controller improvements with additional sensors. Task 3.1 included measures to reduce tower and blade loading, including by using LiDAR-assisted control and improved individual pitch control, as well as

advanced controller designs such as model predictive control and enhanced damping of tower modes.

Task 3.2 was concerned with practical field tests using the 7MW Levenmouth demonstration turbine. Two LiDAR systems were installed on the turbine: a forward-facing LiDAR capable of measuring the turbine inflow by means of a laser beam scanning the entire swept area ahead of the turbine, and a rear-facing long-range scanning LiDAR to measure the turbine wake. These LiDARS were using in conjunction with the different controller tests to provide inflow and wake information, and also for an investigation of the flowfield in the induction zone ahead of the turbine, where measurements were used to compare against CFD modelling.

The following experiments were performed in Task 3.2:

- Yaw misalignment tests, useful for wake steering control for wind farms
- Delta control tests, useful for axial induction control for wind farms, power curtailment and some grid ancillary services
- Derating tests, for power curtailment and load minimisation
- LiDAR-assisted control tests, using wind preview information from a forward-facing LiDAR to improve the control action and reduce loads
- Enhancements to the individual pitch control, to further reduce loads and allow the use of cheaper sensors
- Fast frequency response tests, intended to help enhance grid stability in the presence of a high penetration of renewables

4.2 A short description of the deliverables carried out in WP3

The following five deliverables describe the achievements of Task 3.1:

- D3.1: 7MW turbine model and reference load set. This reports on the aeroelastic model developed for the 7MW turbine, which was used for the controller adaptations developed as part of Work Package 3. The model was used to generate a full set of baseline reference loads for the turbine.
- D3.2 is in two parts, each describing a particular adaptation concerned with active power control and the provision of grid ancillary services. The first part is concerned with alternative ways to curtail turbine output, so that the turbine loads can be minimised by using different combinations of blade pitching and rotor speed reduction. The algorithm was tested in simulations using modifications to the actual turbine controller software, in readiness for field testing in Task 3.2. The second part was concerned with the provision of fast frequency response as an ancillary service by changing the control system of the wind turbine power converter, to make it act like a Virtual Synchronous Machine.
- D3.3 is concerned with active damping of tower loads. A high-resolution model was used to investigate ways to adjust the tower base fatigue loading by balancing fore-aft and side-side vibration, and also to investigate ways to control the wave-induced loading when the

turbine is idling, especially by controlling the nacelle direction and taking account of wind-wave misalignment.

- D3.4 covers the development of a Model Predictive Controller (MPC) in an automated way, starting from high-order linear models derived directly from the Bladed aeroelastic code over the whole operating range, including the rated transition, and developing new methods to achieve an appropriate level of model order reduction. A Matlab implementation was linked directly to a Bladed simulation for testing. The method was developed with a 2MW generic turbine, then applied directly to the very different Samsung 7MW without any need for tuning.
- D3.5 describes two techniques aimed at load reduction, especially tower and blade loads. The first part describes a LiDAR-assisted control (LAC) algorithm, designed to achieve smoother pitch action by making use of the preview measurements of the approaching wind from the upwind scanning LiDAR. The second part describes two enhancements of individual pitch control (IPC). The first enhancement introduces second-harmonic (2P) IPC in addition to the existing 1P IPC, which has the effect of reducing the fatigue-driving blade passing frequency component of fixed-frame loads; the second enhancement is to use tower top rather than blade root strain gauges, as they are likely to be cheaper and more robust. Both the LAC and IPC algorithms were tested in simulations using modifications to the actual turbine controller software, in readiness for field testing in Task 3.2.

The achievements of Task 3.2 are described in four deliverables:

- D3.6 describes the design, installation, commissioning and testing of the two LiDAR systems which were installed on the 7MW turbine for the field tests: the upstream "Spinner LiDAR" which samples the turbine inflow using a complex rosette-shaped scanning pattern, and the rear-facing long-range LiDAR which scans in a horizontal plane behind the turbine.
- D3.7 reports on the field tests of controller adaptations which were carried out on the 7MW turbine. The tests are summarised as follows:
  a) Yaw misalignment tests – with particular application to wake steering control on a wind farm, the turbine was run at different yaw misalignment settings in order to measure the power and thrust of the turbine, with the rear-facing LiDAR used to measure the downstream wake development. This required no significant changes to the turbine controller, needing only an offset to be introduced to the wind vane signal to induce a yaw misalignment.
  b) Delta control tests – with application to axial induction control on a wind farm, and also any grid-mandated power curtailment, this algorithm allows the power and thrust to be reduced by a defined amount at any operational wind speed. The rear-facing LiDAR was again used to measure the effect on the turbine wake. The algorithm was not part of the Task 3.1 deliverables, so the design and implementation are described in an appendix to the D3.7 report.
  c) De-rating tests: for curtailment purposes, two different ways to reduce the turbine rated power, which have different effects on the turbine loads, were developed as described in D3.2.

d) LiDAR-assisted control: using the forward-facing LiDAR to provide a preview of the approaching wind, a feed-forward term is added to the controller to help reduce pitch duty and tower loading, as described in D3.5.

e) Individual pitch control tests: the turbine already uses 1P-IPC to reduce 1P blade fatigue loads, using blade root load measurements. Two additional features are tested here, as reported in D3.5, namely the use of potentially cheaper and more robust tower-top strain gauges instead of blade root gauges, and the addition of 2P-IPC to reduce the 3P non-rotating fatigue loads.

f) Fast frequency response tests: As an ancillary service to enhance grid stability in the presence of a high penetration of renewables, the wind turbine controller can transiently alter the active power produced in response to variations in grid frequency. Since this response is programmed in the controller, it can be designed to act in various ways. The algorithm tested includes three different responses: synthetic inertia, where the change in power is proportional the rate of change of frequency to mimic a conventional (e.g. steam turbine) generator; droop response, where the change in power is proportional to the frequency deviation, and a power boost where the power increases by a pre-defined amount for a short time when the frequency drops below some critical threshold. The algorithm was not part of the Task 3.1 deliverables, so the design and implementation are described in an appendix to the D3.7 report.

- D3.8 further develops the MPC controller of D3.4 to the point of being ready for implementation on the 7MW turbine, taking account of all real-world practicalities. This presented many challenges, including low observability of states, lightly-damped modes, very significant uncontrolled disturbances from turbulence and high computational load and design complexity. These were solved using several new techniques in combination: exponential basis functions to allow a long time horizon with few optimisation parameters; feedback and filtering so that critical modes are damped without relying on their states being well estimated by the Kalman Filter; and filtering of periodic disturbances to minimise model-plant mismatch.
- D3.9 reports on the use of the LiDAR, turbine and met mast measurements together with CFD analysis to model the flow in the induction zone in front of the turbine, and validate a simple model for the advection time predicted by a vortex cylinder model which could be of particular use for improving LiDAR-assisted control.

4.3 An overall conclusion of the impact of the WP3 work

Task 3.1 has demonstrated a whole range of different techniques which can be used to improve the control of a wind turbine, not just for its own sake, but also enhance its usefulness as a component of a grid system with a high penetration of renewables, and to allow it to play a role in active wake control, so that it can contribute to the overall performance optimization of a whole wind farm.

Task 3.2 has taken this further by applying these techniques to a full-scale well-instrumented wind turbine in the field. With the aid of sophisticated scanning LiDARs to measure the inflow and wake, the operation of the new controller features has been verified, both in terms of turbine performance and the effects on the turbine wake.

The project has clearly demonstrated how a large wind turbine controller can be adapted for testing significant controller modifications while maintaining the safety and integrity of the wind turbine at all times. Despite many challenges, the experiments have yielded a large amount of valuable data, which will continue to be analysed well beyond the end of the TotalControl project, and further results will be published in due course.

5. WP4 - Closed-loop WP control

5.1 A short introduction to the overall aim of WP4

Work Package 4 of the TotalControl project was concerned with developing wind power plant controllers which help the owner/operator to maximize the profit. In contrast to WP2, WP4 was focused on practical closed-loop control using models of lower resolution that support control decisions in real time.

In Task 4.1, various strategies for dynamic wind power plant control were developed and tested in simulations, while in Task 4.2, wind power plants were studied as parts of a larger system. This included both analysing the interactions with other power plants and developing design guidelines and standards for wind power plant control. Where possible, the TotalControl Reference Wind Power Plant (TC-RWP) developed in TotalControl D1.3 was used for simulation studies.

Task 4.1 was concerned with a number of different wind power plant control features and adaptations covering a variety of techniques with different goals, ranging from frequency support for the electrical grid to power maximisation. The particular features investigated in Task 4.1 are summarised as follows:

- Task 4.1.1 was concerned with wind power plant control for the provision of grid ancillary services. The studied focused mainly with grid frequency support.
- Task 4.1.2 developed a wind power plant algorithm that uses only basic sensor measurements; respects the hierarchy in which the turbine-level controller takes precedence, interacting only via power set-point commands to each turbine; tracks an operator power command at the plant level; and rejects low-frequency loading due to turbulent winds.
- Task 4.1.3 was concerned with predictive control algorithms which (1) track a power trajectory defined by the transmission system operator using axial induction control; and (2) maximise the overall power output from the wind power plant using wake steering.
- Task 4.1.4 investigated an efficient solution for model-based wind power plant control. In particular, a data-driven approach was applied to optimise the operation of the wind power plant.
- Task 4.1.5 was concerned with dynamic wake induction control. The developed controller tracks a dynamically changing thrust coefficient.

Task 4.2 was concerned with closed loop dynamics and design standards:

In subtask 4.2.1 focused on electrical-mechanical-control interactions. This is motivated by a wind turbine being a flexible structure. Its drivetrain consists of a generator, driveshaft, and aerodynamic rotor, and many wind turbine models also include a gearbox. Fluctuations in the generator air-gap torque — the boundary between the electrical and mechanical systems — can excite resonance in both the turbine's flexible structural components, and in the electric grid. One may therefore expect unfavourable electromechanical interactions between the turbine and grid under certain scenarios.

In subtask 4.2.2, a gap analysis of applicable standards for wind farm control was performed showing that they lack a significant number of requirements for certification. Specific features of a control and protection system applying wind power plant control in a wind farm setup were analysed and supplements to the requirements were proposed.

5.2 A short description of the deliverables carried out in WP4

The following five deliverables describe the achievements of Task 4.1:

- D4.1 gives a brief overview of relevant grid codes and describes how wind farms may contribute to both frequency and voltage stability before the analyses focus mainly on grid frequency support. It is investigated how control algorithms implemented at the wind turbine level can be used for frequency support. Related simulations are carried out for the example of the Irish grid system using historical time-history inputs. The last part is concerned with the Virtual Synchronous Machine (VSM) concept. The possibility to provide inertial support directly from power converters was studied.
- D4.2 describes the development of a hierarchical plant controller that aims to track an operator power command at the WPP level and to reject low-frequency loading due to turbulent winds at individual turbines. The plant control respects the hierarchy in which the turbine-level controller takes precedence, interacting only via power set-point commands to each turbine. The control algorithm is based on parallel control loops along with look-up tables and gain scheduling, and its simplicity and effectiveness make it well-suited for industrial applications.
- D4.3 is concerned with a model predictive controller (MPC) for active power control. The MPC is able to track the power reference requested by the transmission systems operator (TSO). This is done by axial induction control. In particular, the MPC was developed based on a dynamic Fuga model, that can offer fast, accurate and time-varying flow predictions. In the second part, another closed-loop farm controller is developed based on a Gaussian Wake Model. By including feedback from high-fidelity simulations, the engineering model is tuned online to improve its performance. Its effectiveness is shown by online optimization of the yaw angle of individual turbines for the TotalControl wind power plant for the purpose of maximizing the power output.
- D4.4 covers the development of a surrogate model-based control algorithm for WPP control problems. Specifically, a data-driven method, Bayesian optimisation with Gaussian process, is used to construct a surrogate to model the non-convex function of typical wind farm

control objectives. Based on the surrogate, wind farm operation is optimised and coordinated by derating the power output of individual turbines.

- D4.5 describes a controller that was developed to track a dynamically changing thrust coefficient set point to showcase the advantages and disadvantages of dynamic induction control. Using an aeroelastic solver in large eddy simulations, the effectiveness of the controller in tracking a time varying thrust signal was shown for the upstream turbines in the TotalControl Reference Wind Power Plant. The benefits of power gains due to improved wake mixing was compared against the large increase in fatigue loads in turbine components, highlighting the challenges of dynamic induction control.

The achievements of Task 4.2 are described in two deliverables:

- D4.6 is concerned with electrical-mechanical-control interactions of wind power plants. The first part is concerned with reactive power provision by a wind power plant whose control system includes an optimization of the flow dynamics for power maximization. In the second part, an analysis of a power system consisting of a wind power plant, a thermal plant and a hydroelectric power plant was performed showing that the wind turbines' tower modes are felt by the thermal plant, which could be problematic in the event that the turbines' vibrations were synchronized.

- D4.7 reports the analysis of existing standards relevant for wind farm control. It showed that the applicable standards lack a significant number of requirements for wind farm control certification affecting the control and protection system and the load assumptions of the wind turbines respectively wind farms. The specific features of a control and protection system applying wind power plant control in a wind farm setup were analysed and supplements to the requirements were proposed.

  Furthermore, present limitations regarding load case definition and calculation were discussed. Wake models available at present were partly considered insufficient. While tools for wind farm simulation still required more thorough validation, approaches to proceed under the given conditions were developed and documented. Guidance on how to define design load cases for wind farm control was established.

  Grid code compliance (GCC) features relevant to wind farm control were described with their impact on wind turbine and wind farm design. Contradictory GCC requirements within different EU countries were identified. Priorities conflicting with respect to the power system, WT control and protection system as well as with optimization goals were elaborated. As a result, certification requirements were proposed.

  Finally, requirements for testing of wind turbines applying wind farm control were summarized. This includes measurements of structural loads, power performance as well as the safety & function tests in the framework of the wind turbine’s Type Testing. The listing was furthermore supplemented by requirements for GCC tests, which comprises the test plan itself, fault-ride-through testing, measurements of the controllability, power quality as well as commissioning.

5.3 An overall conclusion of the impact of the WP4 work

Task 4.1 has demonstrated a number of different techniques for the control of wind power plants which can be used to optimise the overall performance of the plant, not only with respect to power maximisation but also as a component of a grid system that offers frequency support. The investigated strategies for active power control comprise both static axial induction control, wake steering by yaw control and enhanced wake mixing by dynamic axial induction control. For this, approaches using reduced-order physics-based and data-driven models were further developed. This is important to achieve model-based wind power plant control that is computationally efficient. Frequency support by wind power plants was investigated considering both aerodynamic and electrical phenomena of the system.

Task 4.2 has broadened the view by extending this further to a larger perspective by considering the wind power plant as a component of the power system. The analysis of dynamic interactions between a wind power plant and other power plants supports the advent of more power from wind plants in a future with more renewable energy sources where wind farms are expected to play a larger role in power system services. TotalControl developed design guidelines and standards for implementing wind power plant control in real wind farms and thus brought the realization of wind power plant control even more forward.

6. WP5 - Dissemination

The project has strived to take part in, and present project results at the most relevant international conferences dealing with wind farm control and optimisation. Further, the consortium has made several publications as well as short project videos explaining the projects and its results. The Project website contains information on dissemination products delivered in the project.

The project dissemination has suffered greatly from the impact of Covid-19 in the period of 2020 -2022. In this period many conferences were cancelled – in itself this was a blow to the dissemination activities, but even more so as the project was planning to the conferences as a canvas for backdrop project workshops.

Furthermore, a shift in personnel on the dissemination side of the project have had impact on the dissemination planning and coordination.

In the project the following disseminations activities has been made regarding journal papers and conference participation.

6.1 Journal publications

- **Bossanyi, E.**
  Combining induction control and wake steering for wind farm energy and fatigue loads optimization. *J. Phys.: Conf. Ser.* **1037** 032011, 2018
- **Munters, W. & Meyers, J.**
  Optimal dynamic induction and yaw control of wind farms: effects of turbine spacing and layout**.** *J. Phys.: Conf. Ser.* **1037** 032015, 2018

- **Larsen, G. C. & Larsen, T. J., Hansen, K. S. & Chougule, A.**
  Improved modelling of fatigue loads in wind farms under non-neutral ABL stability conditions. *J. Phys.: Conf. Ser.* **1037** 072013, 2018
- **Lu, L. & N. A. Cutululis**
  Virtual synchronous machine control for wind turbines: a review. *J. Phys.: Conf. Ser.* **1356** 012028, 2019
- **Vitulli, J.A., G.C. Larsen, M.M. Pedersen, S. Ott & M. Friis-Møller**
  Optimal open loop wind farm control, *J. Phys.: Conf. Ser.* **1256** 012027, 2019
- **Mikkelsen, T., M. Sjöholm, P. Astrup, A. Pena, G. Larsen, M.F. van Dooren & A.P. Kidambi Sekar**
  Lidar Scanning of Induction Zone Wind Fields over Sloping Terrain. *J. Phys.: Conf. Ser.* **1452** 012081, 2019
- **Mikkelsen, T., M. Sjöholm, P. Astrup, A. Pena, G. Larsen, M.F. van Dooren & A.P. Kidambi Sekar**
  Lidar Scanning of Induction Zone Wind Fields over Sloping Terrain. *J. Phys.: Conf. Ser.* **1452** 012081, 2020
- **Meng, F., A. W. H. Lio & J. Liew**
  The effect of minimum thrust coefficient control strategy on power output and loads of a wind farm. *J. Phys.: Conf. Ser.* **1452** 012009, 2020
- **Lio, A. W. H. & F. Meng**
  Effective wind speed estimation for wind turbines in down-regulation. *J. Phys.: Conf. Ser.* **1452** 012008, 2020
- **Lio, W. H., Larsen, G. C. & Thorsen, G. R.**
  Dynamic wake tracking using a cost-effective LiDAR and Kalman filtering: Design, simulation and full-scale validation. *Renewable Energy*, Vol. 172, 2021
- **Lu, L., Saborío-Romano, O. & Cutululis, N. A.**
  Reduced order VSM based frequency controller for wind farm. *Energies*, Vol. 14, 2021
- **Sørensen, J. N. & Larsen, G. C.**
  A minimalistic prediction model to determine energy production and cost of offshore wind farms. *Energies*, Vol. 14, 2021
- **Göçmen T., Urbán, A.M., Liew, J. & Lio, A. W. H.**
  Model-free estimation of available power using deep learning. *Wind Energy Science*, Vol. 6, 2021
- **Sood, I., Munters, W. & Meyers, J.**
  Effect of conventionally neutral boundary layer height on turbine performance and wake mixing in offshore windfarms. *J. Phys.: Conf. Ser.* **1618** 062049, 2020
- **Lio, W. H., Larsen, G. C. & Poulsen, N.K.**
  Dynamic wake tracking and characteristics estimation using a cost-effective LiDAR. *J. Phys.: Conf. Ser.* **1618** 032036, 2020
- **Larsen, G.C., Ott, S., Liew, J., Laan, M.P. van der, Simon, E., Thorsen, G.R. & Jacobs, P.**
  Yaw induced wake deflection a full-scale validation study. *J. Phys.: Conf. Ser.* **1618** 062047, 2020

- **Eguinoa, I., Kölle, K., Campagnolo, F., Iribas-Latour, M., Meyers, J., Göçmen, T., Duc, T., Astrain, D., Wingerden, J., Bottasso, C. L., Andersen, S. J. & Giebel, G.**
  Launch of the FarmConners Wind Farm Control benchmark for code comparison. *J. Phys.: Conf. Ser.* **1618** 022040, 2020
- **Larsen, G.C. & Pedersen, M. M.**
  Integrated wind farm layout and control optimization. *Wind Energy Science*, Vol. 5, 2020
- **Giebel, G., Galinos, C., Kazda, J. & Lio, W. H.**
  T2FL: An efficient model for wind turbine fatigue damage prediction and cost of offshore wind farms. *Energies*, vol. 13, 2020
- **Pedersen, M. M. & Larsen G. C.**
  The influence of wind farm control on optimal wind farm layout. *Wind Energ. Sci*., 5, 1551–1566, 2020
- **Merz, K., Chabaud, V., Garcia-Rosa, P. B. & Kölle, K.**
  A hierachical supervisory wind power plant controller. *J. Phys.: Conf. Ser.* **2018** 012026, 2021
- **Lio, W. H. & Evans, M.**
  Computationally efficient model predictive control of complex wind turbine models. *Wind Energy*, vol. 25, 2022
- **Sood, L. & Meyers, J.**
  Tuning of an engineering wind farm model using measurements from Large Eddy Simulations. *J. Phys.: Conf. Ser.* **2265** 022045, 2022
- **Sood, L., Simon, E., Vitsas, A., Blockmans, B., Larsen G. C. & Meyers, J.**
  Comparison of Large Eddy Simulations against measurements from the Lillgrund offshore wind farm. *Wind Energy Science*, preprint wes-2021-153, 2022
- **Bossanyi, E., Ruisi, R., Larsen, G. C. & Pedersen. M. M.**
  Axial induction control design for a field test at Lillgrund wind farm. *J. Phys.: Conf. Ser.* **2265** 042032, 2022
- **Bossanyi, E.**
  Surrogate model for fast simulation of turbine loads in wind farms. *J. Phys.: Conf. Ser.* **2265** 042038, 2022
- **Merz, K., Chabaud, V., Garcia-Rosa, P. B. & Kölle, K.**
  A hierachical supervisory wind power plant controller. *J. Phys.: Conf. Ser.* **2018** 012026, 2021
- **Natarajan, A.**
  Damage equivalent load synthesis and stochastic extrapolation for fatigue life validation. *Wind Energy Science*, vol. 7, 2022
- **Wai, H. L., Larsen, G.C. & Thorsen G. R.**
  Dynamic wake tracking using a cost-effective LiDAR and kalman filtering: Design, simulation and full-scale validation . *Renewable Energy*, vol. 14, 2021

6.2 Conference contributions

- **Munters, Wim & Johan Meyers**
  A data-driven flow model for wind-farm control based on Koopman mode decomposition of large-eddy simulations. 71st Annual meeting of the American Physical Society Division of Fluid Dynamic, Atlanta (US), 18-20 November 2018

- **Lu, L., Ö. Göksu & N. A. Cutululis**
  Power Angle Small-Signal Stability Analysis of Grid-Forming Wind Turbine Inverter Based on VSM Control. Proceedings of the 18th Wind Integration Workshop, 2019
- **Giebel, G., G. Larsen, A. Natarajan, J. Meyers, E. Bossanyi & K. Merz**
  TotalControl - Advanced integrated control of large-scale wind power plants and wind turbines. Wind Energy Science Conference 2019, Cork, Ireland, 17-20 June 2019
- **Lu, L.**
  A Virtual Synchronous Machine Control Scheme for Wind Turbines. Wind Energy Science Conference 2019, Cork, Ireland, 17-20 June 2019, Cork, Ireland, 17-20 June 2019
- **Giebel, G., G. Larsen, A. Natarajan, J. Meyers, E. Bossanyi & K. Merz**
  TotalControl - Advanced integrated control of large-scale wind power plants and wind turbines. WindEurope Offshore Conference, Copenhagen, Denmark, 26-28 November 2019
- **Larsen, G.C.**
  Recent developments in wind farm flow modeling and wind farm control, DTU-KAIST International Cooperative Wind Energy Workshop, Ulsan Korea, 21-22 October 2019
- **Lu, L.**
  Power Angle Small-Signal Stability Analysis of Grid-Forming Wind Turbine Inverter Based VSM Control, 18th Wind Integration Workshop, Ireland Dublin, 16-18 October 2019
- **Lu, L. & N. A. Cutululis**
  A Virtual synchronous machine control scheme for wind turbines. Wind Energy Science Conference 2019, Cork, Ireland, 17-20 June 2019
- **Giebel, G., G. Larsen, A. Natarajan, J. Meyers, E. Bossanyi & K. Merz**
  TotalControl - Advanced integrated control of large-scale wind power plants and wind turbines. WindEurope Summit 2019, Bilbao, Spain, 2-4 April 2019
- **Schoot, W., de Boer, W. & Bossanyi, E.**
  Grid Frequency Stability with Wind Power: Irish Case Study Using a New Closed Loop simulation Environment. Proceedings of the 19th Wind Integration Workshop, 2020
- **Giebel, G., Larsen G.C., Natarajan, A., Meyers, J., Bossanyi, E. & Merz, K.**
  TotalControl - Advanced integrated control of large-scale wind power plants and wind turbines. Global Wind Summit 2018, Hamburg, Germany 25-28 September 2018
- **Lu, L.**
  Enhanced Frequency Control Capability from Wind Turbine Generators and wind Power Plants. UPC Barcelona, Spain, 5 September 2018
- **Hille, N.**
  Implications of wind farm control on certification regarding validation and testing. Wind Energy Science Conference, 2021
- **Dimitrov, N., Urban. A. & Christos G.**
  Wind farm power and load optimization with ML-based surrogate models. Wind Energy Science Conference 2019, 17. – 20. June 2019
- **Pedersen, M. M. & Larsen G. C.**
  The influence of wind farm control on optimal wind farm layout. Wind Energy Science Conference 2019, 17. – 20. June 2019

- **Meyers, J., Vitas, A., Sood, I. & Munters, W.**
  Set-up of a reference wind-farm simulation database for testing of turbine and farm control strategies and load scenarios. Wind Energy Science Conference 2019, 17. – 20. June 2019
- **Larsen, G. C., Giebel, G., Natarajan, A., Meyers, J., Bossanyi, E. & Merz, K.**
  TotalControl - Advanced integrated control of large-scale wind power plants and wind turbines. Wind Energy Electric City Conference 2021, 23-25 November 2021
- **Hille, N., Schleeßelmann, R. & Bayo R. T.**
  Implications of wind farm control on certification regarding validation and testing. Wind Energy Science Conference, 2021
- **Bossanyi, E.**
  Simple induction control scheme for wind farms. Wind Energy Science Conference, 2021
- **Hille, N., Schleeßelmann, R. & Bayo R. T.**
  Does Wind Farm Control require updated load case definitions for design and certification? WindEurope Electric City 2021
- **Sood, I., Munters, W., Vitsas, A. & Meyers, J.**
  Design and comparison of turbine controllers for dynamic induction control in a hierarchical wind farm control approach. Wind Energy Science Conference, 2019
- **Sood, I. & Meyers, J.**
  Comparison of Large Eddy Simulations against measurements from the Lillgrund offshore windfarm. Wind Energy Science Conference, 2021
- **Sood, I., Munters, W. & Meyers, J.**
  On the selection of tracking variables at the interface between wind-farm and turbine controllers in a hierarchic wind-farm control approach. EAWE PhD Seminar, 2018
- **Sood, I. & Meyers, J.**
  Extension of an Aeroelastic Actuator Sector Model for wind turbine parametrization in a coupled Large Eddy Simulation framework. EAWE PhD Seminar, 2019
- **Sood, I. & Meyers, J.**
  Extension and validation of a fast boundary layer model for yaw misalignment in wind farms. EAWE PhD Seminar, 2020
- **Das, K., D.H. Minguijon, & N.A. Cutululis**
  Optimization of reactive power dispatch in offshore wind power plants. EERA DeepWind conference, 15 - 17 January, 2020
- **Sood, I., d'Espierres, C. & Meyers, J.**
  An optimal wind-farm control framework for power maximization and load mitigation through wake-steering. EAWE PhD Seminar, 2021
- **Lio, W. H. & Meng, F.**
  Kalman-based interacting multiple-model wind speed estimator for wind turbines. IFAC Proceedings Volume 53, 2021

7. Overall conclusions - achievements compared to expectations

In response to the generic Horizon2020 project expectation/impact list, this chapter summarizes the achievements regarding “Technology-related impacts”; “EU industrial competitiveness and innovation capacity”; and “Environment, society and energy security”.

7.1 Technology-related impacts

Reduce the technological risks for the next development stages

Mitigation of technological risks is embedded in the ‘genes’ of TotalControl by extensive full-scale validation/testing of models developed whenever possible.

In WP1 an extensive full-scale campaign, in which details of the Lillgrund wind farm flow field were resolved in space and time using advanced long range Lidars, were successfully conducted. These flow measurements were complemented by simultaneous WT load measurements. This unique data set were used to validate high- and medium fidelity prediction models (cf. Task 1.2; D1.2).

In WP2 an extensive full-scale campaign was established to validate optimal de-rating of an entire row of WTs ‘designed’ using the numerical platforms LongSim and Fuga. Promising results has resulted from analysis of 3 months of data (cf. Task 2.5; D2.7). To further consolidate these results, it is decided to continue the field test beyond the TotalControl project.

In WP3 various controller adaptations (i.e. wake deflection control; delta control; de-rating based control; LiDAR-assisted control; enhancements to the individual pitch control; and fast frequency response) were implemented and tested on a real turbine in the field, namely the 7MW Levenmouth Demonstration Turbine (LDT) just off the coast of Eastern Scotland (Task 3.2; D3.6, D3.7 and D3.9).

Significantly increased technology performance; improve efficiency; optimize energy capture

Efficiency is, to a large extend, about performance in terms of *improved energy capture* and *reduction of electrical losses*. This is in the core of the control philosophy, and TotalControl activities strive to support this goal. Prominent examples are the activities previously described in Task 2.1, Task 2.2, Task 2.3 and Task 2.5 and associated deliverables (D2.1, D2.3, D2.4, D2.5, D2.6 and D2.7).

Reducing renewable energy technologies installation time and cost and/or operational costs, hence easing the deployment of renewable energy sources within the energy mix; further reduce the cost of wind energy

Load reduction is important in this respect, and D2.6 (cf. Tasks 2.4) of the TotalControl project deals with and assesses the possibility for reduction of OPEX based on maintaining target reliability levels through control.

Nurturing the development of the industrial capacity to produce components and systems and opening of new opportunities

The flow models applied in WP1 constitute a test bench for WPP control development, and these will thus in turn benefit the industry by allowing more performant WPP controller design in the future. These models have been validated against field measurements from the Lillgrund campaign (cf. Task 1.2.1). Similarly, the open-loop WPP control platform in WP2 paves the way for new WPP control opportunities – e.g. optimal balancing of active wake control approaches as based on both WT de-rating and WT yaw actions. In this regard, a numerical study, using the detailed DTU linear CFD solver (Fuga), has been undertaken. Using the Lillgrund case, this study illuminates the perspectives of potential WPP power gain as based on 1) WT de-rating; 2) Wake deflection caused by WT yaw; and 3) *Integrated* de-rating and wake deflection. Results were presented at the WES 2021 conference (https://backend.orbit.dtu.dk/ws/portalfiles/portal/247826534/2021_WESC_Optimal_open_loop_control_of_wind_power_plants2.pdf).

7.2 EU industrial competitiveness and innovation capacity

Strengthening the European industrial technology base, thereby creating growth and jobs in Europe

The results of TotalControl will lead to technological progress for wind farm control, which will support the accelerating growth of the wind energy sector. For the *individual* WPP, the benefits of using the technology developed in the TotalControl project is believed to be as predicted at project start. However, due to the steadily increasing awareness of clean energy sources around the globe – which during the last couple of months has become as relevant as ever – the aggregated impact of TotalControl achievements will increase over the years compared to the expectation at the project start.

Innovation capacity and integration of new knowledge:

The TotalControl consortium brings together knowledge and competencies from both academia, developers and industry. This will ensure that the outcomes of the project will meet the needs of relevant markets. A very tangible example is the decision among the consortia partners SGRE, VT, DNV and DTU to continue and expand the full-scale validation of optimized WPP control schedules following the end of the TotalControl project.

7.3 Environment, society and energy security

Contributing to solving the global climate and energy challenges & Improving EU energy security

Global climate changes are perhaps the biggest challenge for our generation and therefore high on the agenda within the EU. This challenge has recently been accompanied by the urgent need of *securing energy supply* to the EU, realizing that critical dependence of energy supply from political unstable regimes is unsustainable. Wind energy is believed to play a key role in overcoming the above issues, and the outcomes of TotalControl will contribute to build a solid technology base for 'green competitiveness in Europe' and thereby contribute to the creation of jobs in the wind energy community. This will, in the long run, benefit both larger companies and SMEs.

By including the gained knowledge in the 'WPP design chain', the WPP innovation potential is strengthened, and thus in turn leading to increased European competitiveness within the field renewables – here with a focus on wind energy.