Final report

1.1 Project details

Project title	**Concert** – Control and Uncertainties In Real-Time Power Curves Of Offshore Wind Power Plants
Project identification (program abbrev. and file)	ForskEL 2016-1-12396
Name of the programme which has funded the project	ForskEL, part of the Public Service Obligation
Project managing company/institution (name and address)	DTU Wind Energy, Frederiksborgvej 399, 4000 Roskilde
Project partners	Vattenfall A/S, Siemens Gamesa Renewable Energy (previously Siemens Wind Power)
CVR	30 06 09 46
Date for submission	01 / 04 / 2020

1.2 Short description of project objective and results

The Concert project run by DTU Wind Energy, Vattenfall and Siemens Gamesa set out to develop and test wind farm control and its associated uncertainties. The uncertainties of the PossPOW algorithm determining the Available Active Power of a downregulated offshore wind farm were first quantified, then reduced significantly and finally used in high-fidelity simulations. Several improvements were done for Wind Farm Control modelling, such as the use of a turbine specific turbulence intensity, the impact of spatial variance of turbulence or the use of model free artificial intelligence. On the control side, a complete controller framework was developed and used to mitigate loads, optimise dispatch of individual turbines under downregulation and improve the total power output of a wind farm. Additionally, the project improved the use of surrogate models, making advanced and computationally heavy computer models useable for optimization and in real time control.

Målet med Concert projektet var at reducere usikkerheden omkring nedregulerede offshore vindparker, og at udvikle aktiv dynamisk styring af vindmølleparkerne for at minimere lasterne og øge produktionen.
Concert projektets mål var at udvikle og teste styringsalgoritmer for vindmølleparker og bestemme de tilhørende usikkerhed. PossPOW algoritmen blev udviklet i et foregående projekt, og usikkerheden for denne algoritme blev beregnet, reduceret betydeligt og brugt i højt avancerede computermodeller.
Styring af vindmøllepark blev udviklet på forskellige punkter: brug af møllespecifik turbulensintensitet, effekt af den tværgående turbulens og kunstig intelligens metoder. Et komplet styringsværktøj blev udviklet og brugt til at minimere belastningerne på vindmøllerne, optimere driften af de enkelte møller under nedregulering og øge produktionen af den samlede vindmøllepark. Ydermere forbedrede projektet brugen af surrogatmodeller for at kunne anvende avancerede og beregningstunge modeller til optimering og i hurtige styrings modeller.

1.3 Executive summary

With increasing share of wind power, wind power plants are obliged to contribute to the safe operation of the power system through delivery of ancillary services. The predecessor of Concert project, PossPOW (Possible Power of downregulated Offshore Wind power plants, ForskEL 10763) developed a real-time power curve of available power for offshore wind farms for use during downregulation. The available (or possible) active power (AAP) of a wind power plant is the power the turbines could produce if they were not downregulated, i.e. the amount of upregulation potential which can be traded as reserve power or the amount of the lost production during mandated downregulation. Utilising the findings in PossPOW, the Concert project performed a full uncertainty analysis [14] of both the signal and the forecasts needed for real life trading of the reserve power based on a case study agreed with Vattenfall. Using the state-of-the-art deep learning techniques, the quantified uncertainty was further reduced for dynamic (short-term) possible power estimation [11]. Accordingly, the Concert project has filled the gap of uncertainty assessment while modelling the non-supplied generation for compensation when ordered to perform downward regulation. It has also quantified the significance of more certain reserves in the trading market on different scales [9].

The flow model was further developed to ensure smooth interaction with the wind farm controller. The Dynamic Flow Predictor [12] is a fast, control-oriented, dynamic, linear model of wind farm flow and operation that provides predictions of wind speed and turbine power. The model estimates wind turbine aerodynamic interaction using a linearized engineering wake model in combination with a delay process. The Dynamic Flow Predictor was tested on a two-turbine array to illustrate its main characteristics and on a large-scale wind farm, comparable to modern offshore wind farms, to illustrate its scalability and accuracy in a more realistic scale. In the study on the large-scale wind farm, rotor effective wind speed was estimated with a root-mean-square error ranging between 0.8% and 4.1%. In the same study, the computation time per iteration of the model was, on average, 2.1×10^{-5}s, very suitable for controller implementation.

The Concert project also extended the power estimation and developed simple real-time algorithms to estimate the load on the turbines. This enables to find an optimal set point for the asset control to derive the best value from either power sales, reserve power sales or lifetime conservation. The PossPOW algorithm converts the incident wind on the rotor to a free stream wind speed for the upwind turbine, advects it with newly developed real-time wake models to the next turbine and calculates the power of this turbine under normal conditions, taking the local turbulence intensity into account. This turbulence intensity, together with the turbine specific wind speed, is used to assess the loads on a turbine in the wake. While a full load model of the turbine does not lend itself to real-time operational use due to its high complexity, a surrogate of this complex model enables a simpler parameterization of the loads that allows turbine specific calculation of loads and available power production, simultaneously.

The Dynamic Wake Meander model considers the wake of each upstream turbine as a reduced wind speed deficit which is transported downstream driven by large turbulent structures. The model has been extensively validated with dedicated experiments, large-eddy simulations as well as full scale measurements in both single and multiple wake conditions[1,2,3,4] and it is IEC61400-1 standard for covering load and performance simulation of wind turbines. This model complex is extended from its present state investigating control strategies for using active load reduction in wind farms and predict the detailed power and load response in time domain for down regulated turbines operating in wake conditions. The DWM model coupled with DTU aeroelastic code HAWC2 results are then surrogated using in normal and down-regulated operation as input variables with damage equivalent loads (DEL) at individual turbine locations as target parameters. The fast, optimization friendly surrogate model, T2FL [5], demonstrated that the accumulated fatigue damage of turbines can be effectively distributed amongst the turbines in a wind farm using the power curtailment set points.

Within the Concert project, challenges encountered during the provision of frequency support control were thoroughly investigated. The main research questions on how to adjust the operational limitations for down-regulation levels, the "non-optimal functioning of control strategies in the case of active power limitation" and, the need to develop reliable and accurate methods for estimating the instantaneous possible (available) power have been addressed. The Concert research has come up with methodologies to improve the level of overall WPP uncertainty (performance) under down-regulation by incorporating the estimation of available power algorithm into the design of the WPP controller that optimizes the individual set point distribution, also considering the structural loads experienced by the individual turbines. The results were disseminated in 8 journal papers, 8 conference papers (peer-reviewed), posters and talks, and 3 open softwares [S1] DTU Wind Farm Control framework, [S2] PCE surrogates for power and loads under wind farm control, and [S3] Deep Learning for Available Power Estimation, as well as 1 PhD dissertation. Concert fed into several other projects, most notably the FarmConners EU Coordination and Support Action[5], the TotalControl[6] and Smart4RES EU research projects and the PowerKey ForskEl project.

1.4 Project objectives

The overall objective of the Concert project is to reduce the uncertainty surrounding the down-regulated operation and to provide active dynamic control to optimize the loads and the power production of large offshore wind farms. Concert also originally aimed to demonstrate the results via dedicated experiments on an operating wind farm as well as on the trading market. This aimed to contribute to reach the Danish targets of 50% wind power by 2020 by allowing wind power to play a significant role in ancillary service requirements for stability of the grid.

The operation of a future Danish power system with 100% share of electricity coming from wind will not be possible without assets such of large offshore wind power

[1] Larsen, G.C., Madsen, H.Aa., Thomsen, K. and Larsen, T.J. (2008). Wake meandering - a pragmatic approach. Wind Energy, 11, pp. 377–395. https://doi.org/10.1002/we.267

[2] Madsen, H. Aa., Larsen, G.C., Larsen, T.J., and Troldborg, N. (2010). Calibration and Validation of the Dynamic Wake Meandering Model for Implementation in an Aeroelastic Code. J. Sol. Energy Eng., 132(4). https://doi.org/10.1115/1.4002555

[3] Larsen, T.J., Madsen, H. A., Larsen, G.C. and Hansen, K.S. (2013). Validation of the Dynamic Wake Meander Model for Loads and Power Production in the Egmond aan Zee Wind Farm. Wind Energy, Volume 16, Issue 4, pp. 605–624. https://doi.org/10.1002/we.1563

[4] Larsen, T.J., Larsen, G.C., Madsen, H. A., Thomsen, K. and Petersen, S.M. (2015). Wake effects above rated wind speed. An overlooked contributor to high loads in wind farms. EWEA 2015, Paris.

[5] EU Horizon2020 FarmConners (857844), www.windfarmcontrol.info

[6] EU Horizon2020 TotalControl (727680), www.totalcontrolproject.eu

plants participating in a cost-effective manner to the frequency control. Still as of today, there is no agreed procedure to assess the uncertainty embedded in the available power of a wind farm contributing to the frequency control.

The novelty of Concert is that it benefits from the verified real-time wind farm power curve estimation and investigates all the possible uses of it. First, Concert quantifies and proposes methodologies to reduce the uncertainty of the wind farm scale available power. Furthermore, via the real-time load-aware power curve for the wind power plant, Concert develops down-regulation strategies to optimize the power output and the loads on the turbines as well as to minimize the previously quantified uncertainty in the available active power through set-point management, real-time.

The project was structured in 5 research work-packages, and one work-package dedicated to management and dissemination activities. The main objectives of the work-packages are:

<u>WP0: Management and Dissemination</u>

- to ensure professional implementation of the activities and management of the project. This includes monitoring project progress, organizing consortium meetings, supervision of the quality of the results and the budget, timely submission of deliverables, and reporting.
- to gain widespread acceptance for the scientific results of the project, which will be communicated through the internal and external webpage, presentations in relevant peer reviewed journals, conferences and workshops for stakeholders, i.e. TSO and utility companies.

<u>WP1: Preparation, Market investigation, Literature Review</u>

- to select appropriate model(s) of uncertainty quantification (UQ), propagation and reduction for the real-time power curve.

<u>WP2: Estimation and Mitigation of Uncertainty</u>

- to construct an extensive uncertainty approach to the previously developed real-time power curve;
- to deliver an assessment of the contribution of the wind farm available power uncertainty to the un-certainty of the forecasted available power.

<u>WP3: Multi-Objective Wind Power Plant (WPP) Control</u>

- to develop Wind Power Plant control that will combine several objectives:
  - increase power production through down-regulation of the upstream wind turbines,
  - extend wind turbines lifetime through better load management and
  - provide cost efficient upward regulation taking uncertainties into account by optimizing the individual wind turbine set points.

<u>WP4: Verification, Robustness and Trading Market Aspects</u>

- to verify the power, load and economic outcome of the controller framework developed in WP3, and of the reduced uncertainty of the real-time and forecasted power from WP2.

Throughout the lifetime of the project, all the milestones attached to technical work packages WP1, WP2 and WP3 were completed early or on time. The content of WP4, however, needed to be refined as the originally planned demonstration activity to test and validate the final control algorithm via full-scale downregulation experiments was cancelled due to high risk assessed by Vattenfall for the given timeline. Additionally, several larger scale, European level demonstration projects were planned, which should have trialed all wind farm control concepts developed in Concert and other projects. Most notably, the CarbonTrust Offshore Wind Accelerator run Wind Farm Control Trials project, co-funded by national funders in the UK and the Netherlands and the EU DemoWind scheme, aimed at running a one-year test of various Wind Farm Control (WFC) schemes in a full-scale offshore wind farm with extensive instrumentation. Since this project proposed to do the verification planned for Concert much better than we could, we decided to use the Concert project to go deeper into the uncertainty and robustness of the controllers and control approaches. TotalControl is an EU Horizon2020 project on WFC and wind turbine control currently run by DTU Wind Energy, also with Vattenfall and SGRE as partners. The refined context has been developed within the consortium, which is then communicated and approved by the funding agency EUDP. However, during the lifetime of the Concert project it was not possible to find a suitable wind farm for the DemoWind WFCT project, and it was eventually cancelled. We are currently discussing some full-scale tests in the TotalControl project though.

1.5 Project results and dissemination of results

The **activities** carried out during the project as well as technical results are summarized per work package in the following.

WP0: Management

The targeted activities in this work package were:

<u>0.1 Reporting and Management</u>

This activity concerned the contractual duties of the project manager.

<u>0.2 Employment of personnel</u>

The PhD student and up to three Post-Docs have to be recruited at the beginning of the project. DTU Wind Energy is to consult with the partners on the details of the job adverts, but otherwise work autonomously in hiring the researchers.

<u>0.3 Dissemination</u>

The dissemination and outreach activities to increase the visibility and impact of the Concert project, both in Danish and international levels.

The reporting and general management, as well as the employment of personnel was successfully addressed within WP0 activities. Dissemination activities are listed per work packages down below. (Note that some of the highlights are already included in the executive summary to provide enhanced context.)

<u>Milestones:</u>

M0: The PhD students and Post-Docs are hired.
One PhD and one PostDoc is hired within the Concert project.

<u>Deliverables:</u>

D0.1: Project financial statements and progress reports for Energinet.dk.
Delivered.
D0.2: Final report on the project outcomes.
Refers to this document.

WP1: Preparation, Market investigation, Literature Review

The targeted activities in this work package were:

<u>1.1 Comprehensive literature survey on UQ, propagation and reduction techniques</u>
(DTU Wind Energy, Vattenfall, Siemens)

This activity provided an overview of the industrially applied standardizations, regulations, etc. as well as the state of art in the computational approaches for UQ, propagation and reduction techniques.

1.2 Selection of candidate models and preliminary application using the historical data (DTU Wind Energy)
According to the literature survey and the existing PhD project on wind farm flow model uncertainty, this campaign included a preliminary implementation of the selected approaches for UQ and reduction to the historical data.

Early in the project, a comprehensive literature survey on the uncertainty quantification and reduction for wind farm flow models[7] and wind turbine response [e.g. 8] is performed. Accordingly, classical frequentist methods such as Monte Carlo and bootstrapping were applied to quantify the uncertainty in the real-time power curve algorithm [18]. The potential application of more advanced Bayesian algorithms for online learning in physics-based methods, as well as purely data driven techniques such as deep learning (neural networks) were investigated and made ready for WP2. Therefore, the results in WP1 were fully aligned with the original objectives that are:
− Selection of relevant models for UQ, propagation and reduction
− Preliminary application of the selected techniques to the historical data

Milestones:
M1: The existing UQ and reduction techniques are reviewed, studied and first trials of the selected models are performed.
Achieved, as stated above.

Deliverables:
D1.1: Report on conventional and theoretical procedures towards UQ, propagation and reduction techniques in wind energy applications.
A comprehensive PhD thesis focusing on UQ for wind farm models[7] is used as reference.
D1.2: Report on the first implementation the relevant UQ and reduction procedures.
Presented and published with a title of "Uncertainty Quantification of the Real-Time Reserves for Offshore Wind Power Plants" [18].

WP2: Estimation and Mitigation of Uncertainty

The targeted activities in this work package were:
2.1 Completion of the uncertainty quantification for the real-time available power (DTU Wind Energy, Vattenfall, Siemens)
In this section, the UQ methodology was finalized based on the preliminary results provided in activity 1.2 for the previously developed real-time AAP signal. More curtailment events are used for the initial validation process.
2.2 Convolution of the uncertainty embedded in the real-time power curve and the forecast available power (DTU Wind Energy)
The objective of this element was to bring together the UQ approaches for the real-time and forecasted available power to construct a common uncertainty frame for the reserve power.

[7] Murcia Leon, J. P. (2017). Uncertainty quantification in wind farm flow models. PhD thesis. DTU Wind Energy.
[8] Murcia Leon, J. P., Réthoré, P-E., Dimitrov, N. K., Natarajan, A., Sørensen, J. D., Graf, P., & Kim, T. (2018). Uncertainty propagation through an aeroelastic wind turbine model using polynomial surrogates. Renewable Energy, 119, 910-922. https://doi.org/10.1016/j.renene.2017.07.070

2.3 Enhancement of the available power algorithm (both forecast and real-time) using machine learning uncertainty reduction techniques (DTU Wind Energy, Vattenfall, Siemens)
This activity aimed to reduce the quantified uncertainty of both the real-time and the forecasted available power in sections activity 2.2 using the techniques studied in 1.1.

Further in the project, the estimation and reduction of the uncertainty in the AAP estimation was performed. The first and the second milestones for review and implementation of the uncertainty quantification methods to the real-time available power estimation module was published as an open access article in Wind Energy journal, Possible power of down-regulated offshore wind power plants: The PossPOW algorithm [7]. Covering milestones 3 and 4, the quantified uncertainties in the real time available power algorithm inputs were introduced to the machine learning platform to provide 1-min ahead predictions (very short-term available power forecasts). A benchmark case with 3 different offshore wind farms was defined and a significant improvement compared to the physics-based engineering models for power predictions was observed. The results were published as open-access in Journal of Physics, titled: Data-driven Wake Modelling for Reduced Uncertainties in short-term Possible Power Estimation [11]. Since those publications present the convolution of uncertainty for real-time and short-term forecast, as well as the test and validation cases for the uncertainty reduction in available power predictions, the deliverables of WP2 were successfully completed.

The architecture of the Concert machine learning platform for available power prediction is now implemented for delta control in HAWC2 (DTU aero-servo-elastic tool) and a significant improvement in reserve provision is observed. The results are submitted to the Wind Energy Science open access journal [1].

Therefore, the results in WP2 are fully aligned with the original objectives that are:
− Complete uncertainty model of the real-time power curve and/or wind farm scale available power.
− Contribution assessment of the real-time available power estimation uncertainty to forecast available power.

Additionally, the generated learning platforms, both the online learning for physics-based models using Bayesian updates [14] and deep learning with long-short-term memory recurrent neural networks [11, 1] are becoming go-to toolboxes [S3] for other wind energy applications (*e.g.* underperformance analysis and blade defect forecasting).

Milestones:
M2: The UQ algorithm for real-time AAP is finalized and validated.
Achieved, as described above.
M3: Real-time AAP uncertainty is convoluted with forecast uncertainty: A joint UQ module for the reserve power is built.
Achieved, as described above.
M4: The quantified uncertainty in the reserve power is reduced, tested, validated.
Achieved, as described above.

Deliverables
D2.1: Paper on the convoluted uncertainty in reserve power (both real-time and forecast)

D2.2: Paper on the test and validation cases of the uncertainty reduction in reserve power module
Both of the deliverables are included in the publications listed above [1, 7, 11, 14], as well as the open source toolbox [S3].

WP3: Multi-Objective Wind Farm Control

The targeted activities in this work package were:
<u>3.1 Real-time load estimation procedure</u> (DTU Wind Energy, Siemens)
The Concert controller needs a WPP model to run in real-time mode thus enabling the online decision making. This activity is to focus on the real-time application of the Dynamic Wake Meander model via multi-dimensional look-up table(s) under different operational conditions to be concurrently used in the WPP controller together with the real-time power curve.
<u>3.2 Development of WPP controller</u> (DTU Wind Energy, Vattenfall, Siemens)
The WPP controller is optimizing the WT individual active power set-points aiming at maximizing the overall WPP power production. This is basically done modifying the wake effects on the down-stream wind turbine by down-regulating the upstream ones. By doing so, the wind turbine fatigue loads are also reduced. It was envisaged that optimal control techniques such as Model Predictive Control (MPC) are most suitable for this. A specific focus in this task was to be on determining the value of using advanced measuring devices such as LIDAR for wind speed predictions, in addition to local wind turbine SCADA measurements: pitch angle, rotational speed, generator torque, etc. Finally, the possibility of using the available power of the down-regulated turbines for providing very fast active power increase for frequency control was to be investigated. A second objective of the WPP controller would be to minimize the power losses when the WPP is operating in down-regulated mode, such as "delta power constraint" as defined in the Danish grid code. The purpose of the optimized control is to utilize the possibility of diverse set points of the different wind turbines, and thus minimize the total power losses, while ensuring that the WPP can deliver the active power reserves when needed and with high accuracy.
<u>3.3 Integration and implementation of the dynamic WPP controller</u> (DTU Wind Energy, Vattenfall, Siemens)
While the previous task developed the controller, this task was preparing the WPP controller for actual implementation in the chosen target wind farm.

The development of the DTU Wind Farm Controller framework was completed and successfully disseminated internally in DTU Wind Energy. The framework comprises a variety of wind farm controller for all wind farm operation modes, that is nominal operation and downregulated operation. The framework further contains procedures for online measurement processing, data storage, and wind farm operation modelling. The framework and its novel approaches for wind farm control were published in the PhD Thesis "Multi-objective Wind Farm Control" [8].

Amongst these approaches is the newly developed Dynamic Flow Predictor, which was published in the open-access journal Energies under the title "Fast Control-Oriented Dynamic Linear Model of Wind Farm Flow and Operation" [12]. The Dynamic Flow Predictor is a fast control-oriented dynamic linear model for wind farm operation. Simulations show that the model can accurately capture the dynamics of wind speed and turbine power, while being computationally at least two orders of magnitude faster than comparable models in literature.

For the real-time load estimation procedure, a two-turbine surrogate model for loads was developed and published as open access in Energies under the title "T2FL: An Efficient Model for Wind Turbine Fatigue Damage Prediction for the Two-Turbine Case." [5]. The model uses a set of high-fidelity load calculations using the DTU tool HAWC2 in normal and down-regulated operation, and learns how to interpolate between the points using artificial intelligence techniques. This surrogate model is much faster than the high-fidelity simulations, and can therefore be used for optimization. An example of the combined load optimization of a two-turbine wind farm is calculated with the model, showing good agreement with the high-fidelity simulations. The results show that the downstream turbine producing more power than the upstream turbine is favourable for minimising the load. In addition, simulation results further demonstrate that the accumulated fatigue damage of turbines can be effectively distributed amongst the turbines in a wind farm using the power curtailment and the proposed surrogate model.

Next, a novel approach for power control was developed, which uses a combination of closed-loop feedback control and model-predictive optimization. Simulations show that the approach allows to reduce fatigue loads of the wind turbine tower by up to 30% and increase the accuracy in following the reference for the total power of the wind farm by up to 45%. The approach was published in IEEE Transactions on Control Systems Technology under the title "Model-optimized Dispatch for Closed-loop Power Control of Waked Wind Farms" [4]. The performance of the newly developed power controller was also disseminated in oral presentations at the Wind Energy Denmark 2018 conference and the Wind Energy Science 2019 conference. Recently, an investigation on "Mitigating Impact of Spatial Variance of Turbulence in Wind Energy Applications" is published in the open-access Wind Energy Science journal [2]. The work investigates the spatial variance of turbulence and approaches to mitigate its impact on wind energy applications such as wind farm control and wind turbine performance measurements. Furthermore, the study on the mitigation of fatigue loads of wind turbines using simulation databases is presented in the DeepWind conference in Trondheim, Norway [13].

Given the promising results obtained with yaw steering wind farm control in literature, the DTU CFD platform Ellipsys3D has been further extended to include the capabilities of yaw misalignment. Using both the steady simulations in RANS and the dynamic simulations in LES, the potential power gain and the corresponding structural loads have been calculated. To take the uncertainty into account, the novel concept of 'power gain likelihood' has been developed and recently published in the open-access journal Wind Energy Science [3]. The two Vestas V27 setup (based on SWIFT experiments performed by SANDIA) has been established as the test case. The results show that when the model bias and the uncertainties are taken into account, the power gain likelihood reduces significantly. For the near wake (<5D turbine spacing) less than 2% gain is to be expected where for larger distances, there is essentially no benefit of yaw steering optimization. The study will be expanded for larger turbines and multiple turbine configurations where the verification approach of power gain likelihood is to be further implemented in FarmConners benchmark[9] and TotalControl[10]; two European Commission H2020 wind farm control projects lead by DTU Wind Energy.

[9] https://www.windfarmcontrol.info/benchmark

[10] https://www.totalcontrolproject.eu/modelling-and-validation

Therefore, the results in WP3 are fully aligned with the original objectives that are:
- Develop Wind Power Plant control that will combine several objectives: increase power production through down-regulation of the upstream wind turbines, to extend wind turbines lifetime through better load management and to provide cost efficient upward regulation taking uncertainties into account by optimizing the individual wind turbine set points.

<u>Milestones:</u>
M5: The Dynamic Wake Meander model is adjusted, tested and validated for real-time load estimation under different operating conditions.
Achieved, as described above.
M6: WPP controller testing in simulation environment is finished
Achieved, as described above.

<u>Deliverables:</u>
D3.1: Report on the real-time models used in the WPP controller
Delivered on the listed publications above [2, 3, 5, 12].
D3.2: Report on the WPP controller development and simulation
Delivered on the listed publications above [3, 4, 5, 8, 13].

WP4: Verification, Robustness and Trading Market Aspects
As mentioned already in section 1.4, WP4 was changed from the originally intended full-scale WFC experiment at a large-scale offshore wind farm to a more supportive role for the other planned measurement campaigns. The updated activities in this work package were:
<u>4.1 Validation of the Wind Farm Controller and its modules</u>
This activity aimed to provide evidence on the possible value of the multi-objective controller developed in WP3. This includes a proper validation of the plant models used in the simulation scenarios using additional data and possibly actual experiments on an onshore or offshore wind farm. It also should show a possible power production increase and/or a decrease in mechanical loads for typical scenarios. Typically, the simulation scenarios then must include the following:

- Control scenarios showing power production increase
- Control scenarios showing load decrease (without decrease in power production)
- Simulation scenarios and metrics showing the validity of the used plant model
- Simulation scenarios showing that the control solution is robust to model and measurement errors. This includes not only that the stability must be maintained but also that the performance does not degrade too much (preferably not at all). After all, there will always be a deviation between the model used by the controller and the real plant.

In order to properly show the above, the following has to be considered:

- The major part of the wind rose must be covered
- If the plant model is calibrated using plant data, a different data set must be used for the validation
- The plant model should preferably be for the same plant as the one indented to use in the field test
- The plant model used in the simulator should not be the same as the one used in the optimal controller (typically a high-fidelity model is used for the plant and a simplified in the optimal controller).

- If internal control signals of the turbine controller are to be adjusted by the optimal controller, a proper turbine model may be required, otherwise a black-box model may be sufficient

In order to achieve the above, good measurement data from one or several wind farms is required.

4.2 Convolution of short-term forecasting uncertainties with PossPOW uncertainties

For trading reserve power for the day ahead, the uncertainty of the PossPOW algorithm is to be convoluted with the uncertainty of the day-ahead forecast.

4.3 Evaluation of the use case of the Concert models in trading

The business model and market position of the PossPOW and Concert algorithms is to be assessed using historical data. The advantage of the less uncertain provisions is to be shown in comparison to the pre-existing version.

For Task 4.1, the test cases and the validation summary of the developed WFC and its submodules are explained under WP3 activities, which are summarized in two journal publications: "T2FL: An Efficient Model for Wind Turbine Fatigue Damage Prediction for the Two-Turbine Case" [5] and "Model-optimized Dispatch for Closed-loop Power Control of Waked Wind Farms" [4].

For Tasks 4.2, together with the activities in IEA Wind Task 36 Forecasting (where Gregor Giebel is the Operating Agent), the uncertainty module in Concert real-time available power is extended to SCADA based wind power forecasting for several forecast horizons. A concurrent day ahead forecasting scheme with 5min resolution is created and applied for several test cases using Horns Rev-I wind farm operated by Vattenfall. Additionally, the workflow is extended further to incorporate price forecasting including the hybrid plant scenarios[11]. Currently, in collaboration with ConWX, which is a Danish weather and energy forecasting company, the deep learning based Concert forecasting scheme is further trained to include numerical weather prediction in addition to the SCADA. The final objective is to improve the current ConWX commercial forecasts with utilization of state-of-the-art neural networks and transfer learning algorithms. Thanks to expertise built in Concert, DTU Wind is the preferred partner in such an objective.

For Task 4.3 which aims to perform the economic assessment of more certain reserves in the trading market, a case study based on Nordpool DK1 market was constructed. A 2-hours period in February 2019 with relatively low available power in the wind and higher reserve prices was selected. The more certain reserves predicted by the deep learning methods in the Concert/PossPOW algorithm are shown to be economically beneficial in the order of 4% compared to persistence methods for the investigated 2-hours. The time dependency of the uncertainty in the reserves is also investigated. This SCADA based recurrent neural network training methodology and the results of the corresponding trading case study is presented to the Concert project partners and published [9]. The study will be further enhanced with the newly available data in FarmConners project (EU coordination action mentioned earlier), within its Market Showcase of wind farm control activities before final publication.

Therefore, the results in WP4 are fully aligned with the original objectives that are:

[11] Grapperon, A. L. T. P. (2019) Optimal hybrid park control strategy. MSc Thesis (currently being prepared for journal publication)

- to verify the power, load and economic outcome of the controller framework developed in WP3, and of the reduced uncertainty of the real-time and forecasted power from WP2.

Milestones:
M7: Verification strategy decided
Achieved, as described above.
M8: Trading assessment performed
Achieved, as described above.

Deliverables
D4.1: Report describing the verification experiments
D4.2: Report describing the verification results
D4.1 and D4.2 are published in conjunction with WP3 deliverables [2, 3, 4, 5, 8, 12, 13].
D4.3: Paper on the economic assessment of more certain reserves in the trading market
Published as a working paper [9], to be extended with newly available data in FarmConners project as described above.

1.6 Utilization of project results

DTU is already using the results for further education and research. In the EuroStars WISDOM project, new PhD student Jaime Yikon Liew took over the code from Jonas Kazda (the PhD student of Concert), integrates it into the tool chain that DTU Wind Energy usually employs, and will use the Dynamic Flow Predictor to estimate the wind flow in a wind farm based on novel radar measurements. In the EU Coordination and Support Action FarmConners, Tuhfe Göçmen and Jaime will use the DTU Wind Farm Controller to calculate the benchmarks given by FarmConners. The HAWC2 parameterisations might be employed in the EU research project TotalControl. Paul Hulsman's code is used in further MSc thesis projects, also with our industry partners. Generally, the code and knowledge produced will go into other research project in the realm of Wind Farm Control. The Concert project also put DTU sufficiently on the map of Wind Farm Control research, that we could activate most of the renowned scientist and industry to join the FarmConners collaboration network, with the intention to land an IEA Wind Task on WFC.
Vattenfall was intrigued by the load results and the connected learnings, and the in-house load engineers are investigating to use the findings. Vattenfall also did an in-house project on the Available Active Power calculation (the PossPOW algorithm) with their trading and markets section, and found that the accuracy of the algorithm was paramount for the benefit. They however also found that the current price for reserve power was too low to make the activation worth while.
Siemens Gamesa Renewable Energy found the model predictive control developed by Jonas Kazda inspiring in its formulation, but the real test of the controller in high-fidelity flow modelling (LES) was missing. This was a clear learning of the project: if one is to try the controller in an actual wind farm, there needs to be a solid upside for the site manager, as well as an assessment of loads impact, otherwise it will not be allowed. However, in order to claim such an upside and impact believably, the controls and modelling need to be quite developed and tested in high-fidelity simulations. Further, Siemens Gamesa builds further on results from wake steering WFC study [3], and performs joint follow-up MSc thesis projects with

DTU on modelling of wake steering[12] and running project with Pim Jacobs. During the project, Siemens Gamesa also launched Wake Adapt, the first commercially available WFC implementation employing wake steering.

The wide-spread implementation of WFC technologies in the existing wind power fleet could probably enable up to 0.5% increased production across the currently installed 205GW of wind power plants in Europe, which would correspond to 2.2 TWh, or the consumption of 600.000 households, saving 1.4 million tons of CO2 yearly. This production in wind power terms is equal to the addition of Kriegers Flak, a 600MW offshore wind farm, for much less than the 1.3 billion euro the Kriegers Flak project has cost. The load reduction potential also available from the controller is not even valorised in this assessment, but to get a year or two more from existing assets would also constitute major revenue. A full implementation of the project across the wind industry would therefore make wind power cheaper, and thus enable the ambitious climate and electrification targets on the Danish, European and world level.

1.7 Project conclusion and perspective

The Concert project set out to develop and test wind farm control and its uncertainties. The uncertainties of the PossPOW algorithm [7] determining the Available Active Power of a downregulated offshore wind farm were first quantified [18], then reduced significantly [11] and finally used in high-fidelity HAWC2 simulations [1]. Along the way, several improvements were done for Wind Farm Control modelling, such as the use of a turbine specific turbulence intensity [6], the impact of spatial variance of turbulence [2] or the use of a model free artificial intelligence model [1]**Error! Bookmark not defined.**. On the control side, a complete controller framework [17] including the Dynamic Flow Predictor [12] was developed and used to mitigate loads [13], optimise dispatch of individual turbines under downregulation [4] and improve the total power output of a wind farm [8]. Additionally, the project improved the use of surrogate models, making high-fidelity (but computationally heavy) computer models useable in real time control, for yawed turbines [3] and for load estimates [5].

The project yielded 1 PhD thesis, 9 journal publications and more than 10 conference contributions. Even more, the project delivered three sets of software to be used in WFC, including the full controller framework.

For the future, a more thorough testing of the developed controller remains, preferably in a high-fidelity modelling suite like Large Eddy Simulation such as DTU's own Ellipsys3D code. Additionally, the comparison of the individual and combined results and modelling approaches with measured data is a gap, which we could not close due to the unavailability of the experimental campaign from the Wind Farm Control Trials project. Another interesting science topic would be to apply the wake models and controller to floating wind farms, an emerging but promising realm.

[12] http://files.safakaltun.com/Safak_Burak_Altun_MSc_Thesis.pdf, also presented at WESC 2019 (https://zenodo.org/record/3371168#.XoLykuozbDA)

Annex

The homepage of the project was www.posspow.vindenergi.dtu.dk.

A.1. List of Concert Publications

[1] Göçmen, T., Liew, J., Meseguer Urban, A., & Lio, A. W. H. Model-free Estimation of Available Power using Deep Learning, *Wind Energy Science*, https://doi.org/10.5194/wes-2019-80 , in review, 2020.

[2] Kazda, J. & Mann, J. (2020) Mitigating Impact of Spatial Variance of Turbulence in Wind Energy Applications, *Wind Energy Science*, https://doi.org/10.5194/wes-2019-10

[3] Hulsman, P., Andersen, S., J. & Göçmen, T. (2020). Optimizing wind farm control through wake steering using surrogate models based on high-fidelity simulations. *Wind Energy Science*, *5*, 309–329. https://doi.org/10.5194/wes-5-309-2020

[4] Kazda, J., & Cutululis, N. A. (2020). Model-Optimized Dispatch for Closed-Loop Power Control of Waked Wind Farms. *IEEE Transactions on Control Systems Technology*. https://doi.org/10.1109/TCST.2019.2923779

[5] Galinos, C., Kazda, J., Lio, A. W. H., & Giebel, G. (2020). T2FL: An Efficient Model for Wind Turbine Fatigue Damage Prediction for the Two-Turbine Case. *Energies*, *13*(6), [1306]. https://doi.org/10.3390/en13061306

[6] Duc, T., Coupiac, O., Girard, N., Giebel, G., & Göçmen, T. (2019). Local turbulence parameterization improves the Jensen wake model and its implementation for power optimization of an operating wind farm. *Wind Energy Science*, *4*(2), 287-302. https://doi.org/10.5194/wes-4-287-2019

[7] Göçmen, T., Giebel, G., Poulsen, N. K., & Sørensen, P. E. (2019). Possible power of down-regulated offshore wind power plants. Wind Energy, 22(2), 205-218. https://doi.org/10.1002/we.2279

[8] Kazda, J. (2019). Multi-objective Wind Farm Control. DTU Wind Energy. https://doi.org/10.11581/dtu:00000044

[9] Göçmen, T. (2019) Deep Learning for Reserve Power Estimation - NordPool DK1 market case study https://doi.org/10.5281/zenodo.3706527

[10] Galinos, C., Larsen, T. J., & Mirzaei, M. (2018). Impact on wind turbine loads from different down regulation control strategies. *Journal of Physics: Conference Series*, *1104*(1), [012019]. https://doi.org/10.1088/1742-6596/1104/1/012019

[11] Göçmen, T., & Giebel, G. (2018). Data-driven Wake Modelling for Reduced Uncertainties in short-term Possible Power Estimation: Paper. *Journal of Physics: Conference Series*, *1037*(7), [072002]. https://doi.org/10.1088/1742-6596/1037/7/072002

[12] Kazda, J., & Cutululis, N. A. (2018). Fast Control-Oriented Dynamic Linear Model of Wind Farm Flow and Operation. *Energies*, *11*(12), [3346]. https://doi.org/10.3390/en11123346

[13] Kazda, J., Merz, K., Cutululis, N. A., & Tande, J. O. (2018). Mitigating Turbine Mechanical Loads Using Engineering Model Predictive Wind Farm Controller. *Journal of Physics: Conference Series*, *1104*, [012036]. https://doi.org/10.1088/1742-6596/1104/1/012036

[14] Göçmen, T., & Giebel, G. (2018). Uncertainties and Wakes for Short-term Power Production of a Wind Farm. In *Proceedings of the 2018 Wind Energy Symposium* American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2018-0252

[15] Kazda, J., Mirzaei, M., & Cutululis, N. A. (2018). On the Architecture of Wind Turbine Control Required for Induction-based Optimal Wind Farm Control. In *Pro-*

ceedings of the 2018 Annual American Control Conference (ACC) (pp. 3074-3079). IEEE. American Control Conference https://doi.org/10.23919/ACC.2018.8431663
[16] Kazda, J., Göçmen, T., Giebel, G., Courtney, M., & Cutululis, N. A. (2016). Framework of Multi-objective Wind Farm Controller Applicable to Real Wind Farms. In *Proceedings of Wind Europe Summit 2016*
[17] Kazda, J., Göçmen, T., Giebel, G., & Cutululis, N. A. (2016). Possible Improvements for Present Wind Farm Models Used in Optimal Wind Farm Controllers. Paper presented at 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, Austria.
[18] Göçmen, T., Giebel, G., Réthoré, P-E., & Murcia Leon, J. P. (2016). *Uncertainty Quantification of the Real-Time Reserves for Offshore Wind Power Plants*. Paper presented at 15th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Vienna, Austria.

A.2. Concert Software Repositories

[S1] Kazda J. et al., *DTU-Wind-Farm-Control-Framework* (DTU internal access), https://gitlab-internal.windenergy.dtu.dk/kazd/DTU-Wind-Farm-Control-Framework
[S2] Hulsman P. et al., *PCE surrogates for power and loads under wind farm control*, https://github.com/Paul1994H/Surrogates-Wind-Farm-Control-Model.git
[S3] Göçmen T. et al., *Deep Learning for Available Power Estimation,* https://gitlab.windenergy.dtu.dk/tuhf/deep-learning-for-available-power-estimation