ENERGINET/DK

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Final report

1. Project title	PossPOW – Possible Power of downregulated Offshore Wind power plants
2. Project identification	Energinet.dk project no. 2012-1-10763
3. Project period (date, year)	01.05.2012-31.03.2016
4. Entity responsible for the project	Technical University of Denmark, Department of Wind Energy (CVR 30060946) Frederiksborgvej 399, 4000 Roskilde
5. Reporting period	Full project

6. Signature of authorised signatory
Date: 15.6.2016
Name: Gregor Giebel
Signature: Gregor G.

7. Project summary

During the application phase of the project, DONG Energy pulled out of the negotiations, but was added later on their own budget as Affiliated Party. Already early in the project, Vestas had come into financial difficulties and could not devote the necessary manpower to contribute to the project. While the door was kept open long for a re-joining of the project, eventually they were dropped from the project. Their main scheduled contribution was for the experiments, which was taken over by Vattenfall – as was the employee who had joined the kick-off meeting for Vestas. Their part in guiding the project to industrial relevance and to come with input and details about modern wind turbines was taken care of by Siemens Wind Power, project partner from the start with own budget. Throughout the whole project, Siemens made valuable contributions of time, data, and especially discussions of the operational envelope of turbines and the flow in wind farms. Vattenfall allowed us to use the Horns Rev-I wind farm for experiments, and conducted those. DONG was available for valuable discussions, both on the meetings and in between.

As far as scientific projects go, the PossPOW project followed the work plan pretty well. The overall structure of problem analysis, algorithm development and experimental verification was kept. The envisaged milestones were kept, allowing for the delayed employment of the DTU PhD student.

The PhD position was publicised in July with a deadline of 10 August. About 75 applications were received, and the coming academic supervisors Gregor Giebel, Poul Sørensen and Niels Kjølstad Poulsen sifted through the applications. Finally on **December 15** the first project milestone was reached when Tuhfe Göçmen, the chosen candidate, started to work at DTU Wind Energy. As part of her education, Tuhfe has taken the *Planning and Development of Wind Farms* (46200) Master course from DTU Wind Energy in January 2016 (5 ECTS). After that, she started a specialized PhD Course named *Wake Modelling* with Pierre-Elouan Réthoré (5 ECTS). Towards the end of the course, she also attended the PhD *Summer School of Remote Sensing for Wind Energy* (2.5 ECTS) for one week. With Niels Kjølstad Poulsen of DTU Compute, she finished another specialized PhD course called *System Identification* (5 ECTS). Additionally, she learned *How to Write a Scientific Paper* (2.5 ECTS).She also attended an external winter school offered by the Eurotech program, entitled *Integrated Approach to Energy Systems* (4 ECTS) which took place in EPFL, Lausanne. As part of her encouraged external stay, she visited the University of Strathclyde, Department of Electronic and Electrical Engineering, Wind Energy Systems Working Group (06 October 2014 – 10 January 2015) in Glasgow, UK. Her host supervisor was Dr. Olimpo Anaya-Lara. Apart from experiencing a brand new and surely exciting research environment, she had the chance to observe different aspects and state of art in wind farm control, on-going industrial and academic research in online data collection and manipulation together with the UK National Grid procedures and market strategies. As part of her teaching activities, she took part in the DTU Wind Energy Master's Course *Planning and Development of Wind Farms* between 06/01/2014 and 24/01/2014. Her PhD thesis was finally handed in on December 14, 2015, and she successfully defended her thesis on March 9, 2016, against a scientific evaluation committee consisting of Jens Nørkær Sørensen (DTU Wind Energy), Jay Apt (Carnegie Mellon University) and Knud Johansen (Energinet.dk).

Since April 1st, 2015, Mahmood Mirzaei worked for one year as a PostDoc at DTU Compute. In this project the concept of wind farm power optimization was also investigated. It was shown through simulations that it is possible to increase the produced power by adjusting reference power and consequently the induced velocities of individual wind turbines in a wind farm. Besides, it was also shown that the generated power in a wind farm depends also on the control strategy of the wind turbines. Wind turbine control strategy determines the steady state operating points as a function of wind speed. It is possible to increase the generated power of the farm even further by choosing appropriate wind turbine control strategies.

The project had the kick-off meeting at Risø on 14 May 2012, and normal project meetings on 29 January 2013 at Risø, and on 20 June 2013 at Vattenfall in Fredericia. An internal project meeting was held on April 30 at Risø to share knowledge and brainstorm with internal partners (e.g. DTU Compute and DTU Elektro). The meeting on 10 December 2013 at Vattenfall in Esbjerg included a tour to their wind farm control centre. Full project meetings were held on 11 June 2014 in Risø, on 20 August 2014 in Brande, which included an interesting tour of the Siemens Windpower plant there, on 23 January 2015 at Vattenfall in Fredericia and on 15 April 2015 at DONG in Skærbæk. The final meeting was on 29 October 2015 at Risø in conjunction with the public final workshop of the project.

The budget has been kept by the partners. The largest parts were the employment of Tuhfe Göçmen and Mahmood Mirzaei, which followed a steady schedule. Vestas share of the budget (as well as the work they were to do) was taken over by Vattenfall for the experimental campaign, as per our request in the Periodic Project Report of 15 August 2015, where also other minor budget adjustments were made. Siemens contributed with man-power and data.

8. Scientific summary

The main scientific report is the PhD thesis of Tuhfe Göçmen. The abstract and some highlight result plots (with caption numbering as in the thesis) are given here, the whole thesis is attached.

The thesis describes an industrially applicable, validated method for the real-time estimation of the possible power of an offshore wind power plant, called *PossPOW Algorithm,* as there is neither a standardised regulation by the TSOs nor a verified approach regarding the wind farm scale available power estimation exist today. The PossPOW algorithm can also be used in the wind farm control as it yields a real-time wind farm power curve.

The modern wind turbines have a possible (or available) power signal at the turbine SCADA system and the current state of the art is to aggregate those signals to achieve the wind farm scale production capacity. However the summation of these individual signals is simply an over-estimation for the wind power plant, due to reduced wake losses during curtailment. Therefore, the primary focus through the study is to correct the “down-regulated” wake within the curtailed wind farm via real-time wake model(s) using 1 Hz SCADA signals from the turbines.

The determination of the possible power with the PossPOW algorithm works as follows: firstly the second-wise upstream (wake-free) wind speed is estimated. Then the upstream wind is introduced into the wake model, adjusted for the same time resolution, to simulate the power losses that would occur during nominal operation. The input 1 Hz turbine data are active power, pitch angle, and rotational speed. The method is validated in Horns Rev-I, Lillgrund and Thanet offshore wind farms, together with NREL 5MW simulations.

Then the reduced wake is to be replaced by the wake model which estimates the velocity deficit for nominal operation. An evaluation of the existing wake models show that the suitable models are tuned for 10-min averaged data. Therefore, the Larsen wake model is re-calibrated for real-time using Thanet data, validated in Horns Rev-I and then implemented in farm scale considering the local turbulence, time delay and meandering. The validation of the algorithm is performed using experiments in Horns Rev-I where two of the upstream turbines are curtailed. The PossPOW algorithm is compared to the current practice and shown to perform significantly better, according to the error scores stipulated in the Danish grid code.

Some highlight results are given below:

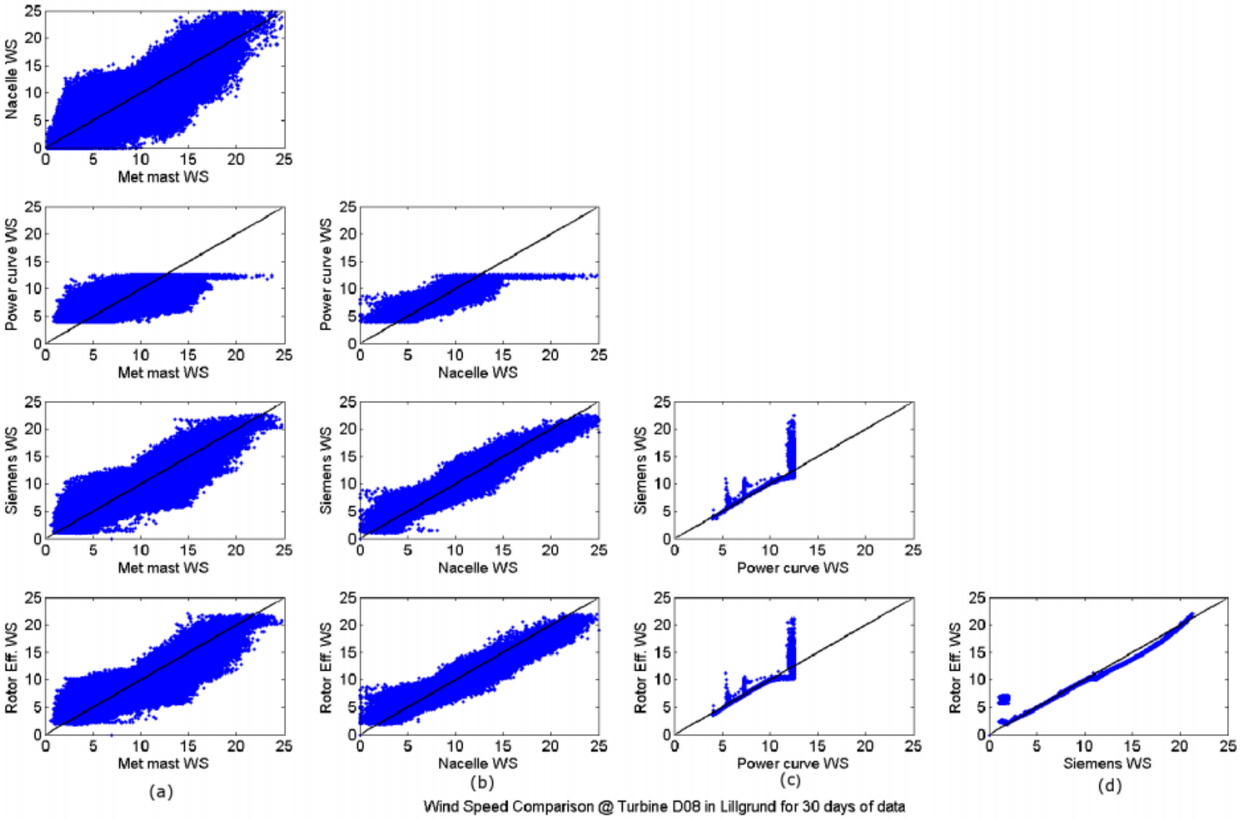

Figure 3.7: Second-wise Wind speed comparison of the measurements taken at the **(a)** met mast *Met mast WS*, **(b)** the nacelle anemometer *Nacelle WS*; and the estimations using **(c)** the turbine power curve *Power curve WS*, **(d)** the manufacturer $C_P(\lambda,\theta)$ *Siemens WS* and **(d)** the approximated $C_P(\lambda,\theta)$ as in Equation 3.2 *Rotor eff. WS*

The rotor effective wind speed is implemented in Lillgrund and compared with the power curve, nacelle wind speed and SiemensWS as well as the high frequency 1 Hz met mast wind speed observations. The developed rotor effective algorithm is seen to successively reproduce the wind speed estimated using the authentic coefficient of power, Cp (λ,θ), table of the Siemens SWT – 2.3 – 93 turbine with a slight underestimation around the rated wind speed where the pitch peaks.

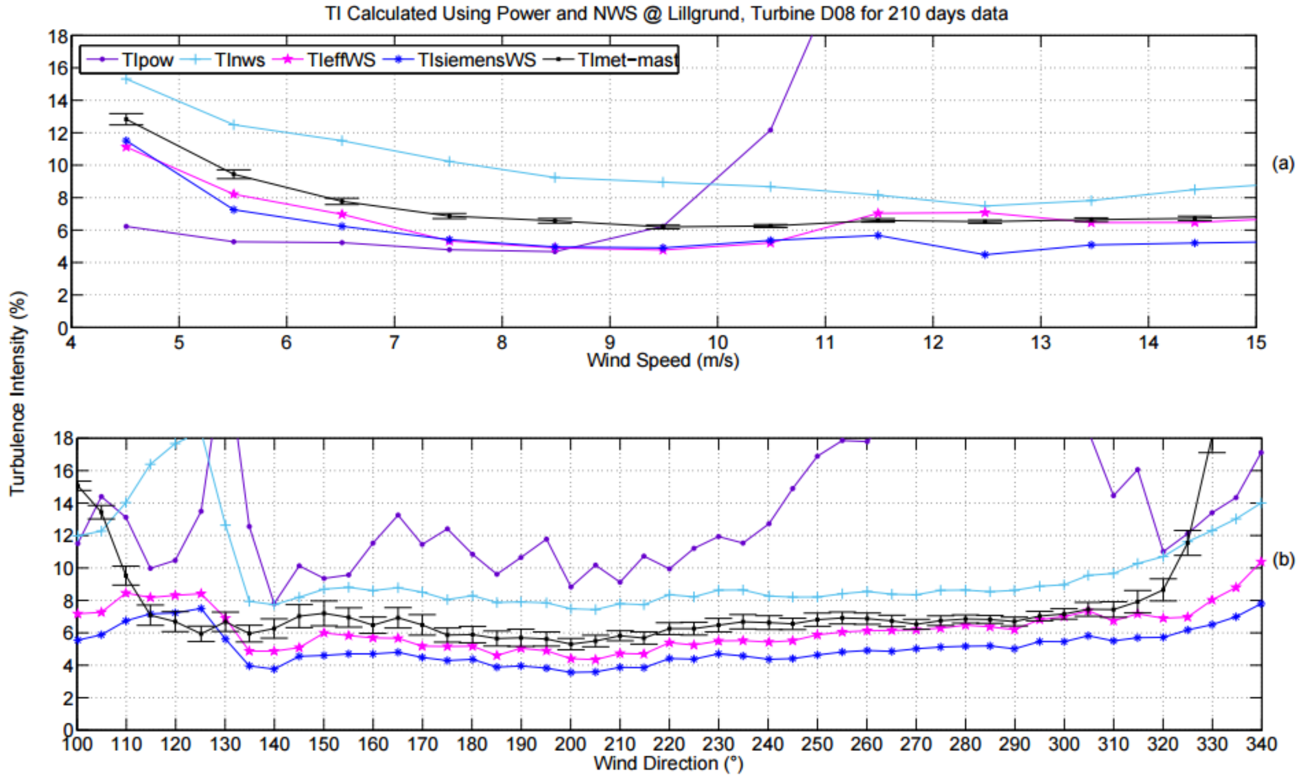

Figure 5.1: Ambient Turbulence Intensity in Lillgrund, presented in terms of (a) the wind speed (b) the wind direction, errorbars indicating 95% normalized confidence intervals

The ambient TI is calculated using the met mast (*TImetmast*) together with the fluctuations in the active power (*TIpow*), nacelle anemometer (*TInws*), Siemens estimated wind speed (*TISiemensWS*), and rotor effective wind speed (*TIeffWS*) at the reference turbine in Lillgrund.
It can be seen from both Figure 5.1(a) and (b), page 52 in the thesis attached, that the *TInws* is higher than the *TImetmast* for all the wind speed and directions, as expected due to the high levels of noise in the signal. Although the TI pow is in a good agreement with the met mast for low speed flows, around the rated wind speed it rapidly increases due to the behaviour of the power curve. The *TIeffWS* on the other hand, seems to be successfully representing the characteristics of the *TImetmast* with a consistent bias similar to the Siemens estimated wind speed. That difference can be explained by the fact that the *TImetmast* is calculated using the point measurements whereas the *TIeffWS* and *TISiemensWS* are considering the wind speed seen by the whole rotor. That automatically includes the geometrical averaging between 21.5 m – 114.5 m, which smooths out the fluctuations in wind speed.

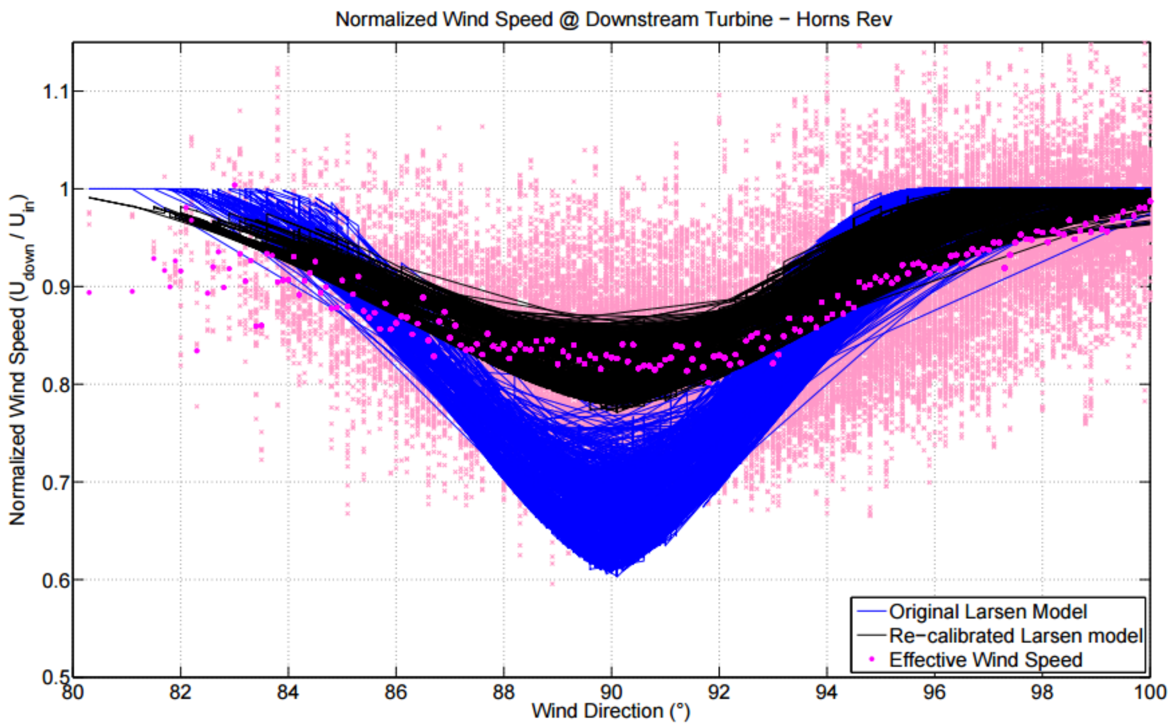

Figure 5.7: Normalised 1-sec wind speed at the downstream turbine, 7*D*, in Horns Rev - Original and Re-calibrated Larsen model together with the raw data and the moving average

The comparison of the original Larsen model and the re-calibrated version for second-wise dataset is presented in Figure 5.7, page 61 in the thesis. Although the data is not symmetrically distributed over the wind direction bin, it can easily be seen that the original Larsen model significantly under-predicts the downstream wind speed for the second-wise dataset. Better recovery achieved by the re-calibration is observed especially for 90°±5° wind direction bin.

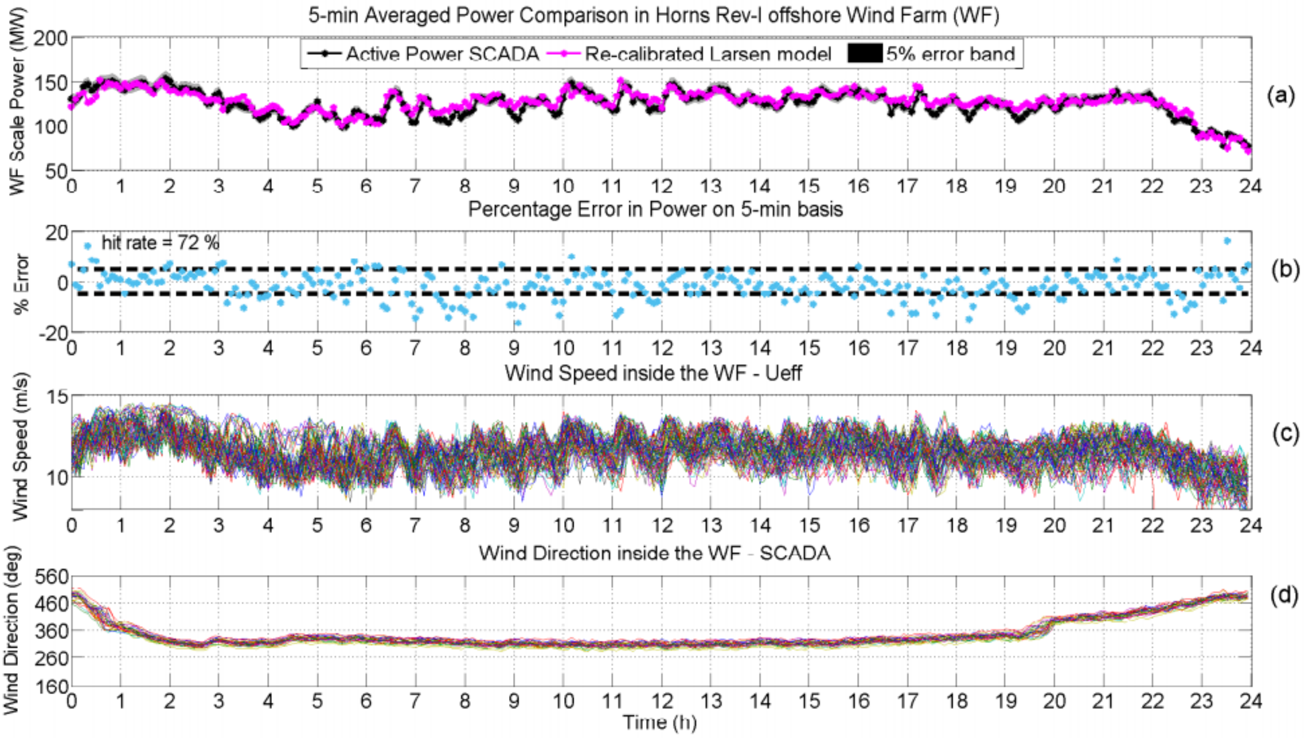

Figure 6.4: (a) 5-minute averaged Active Power (SCADA) and Re-calibrated Larsen model (together with Equation 5.2) results in Horns Rev-I, (b) the estimated effective wind speeds and (c) the wind direction signals at the turbine locations inside Horns Rev, 24-hours data. Wind direction is normalized around 360° due to northerly winds.

The PossPOW algorithm is applied to the normal operational dataset of 24-hours period in Horns Rev.-I. The turbines are exposed to north-westerly winds during that investigated period, which corresponds to diagonal wakes with higher upstream turbine distances. The wind speed is slightly lower than the rated with fairly steady wind direction during the most of the dataset.

Similar to any other wake model, the PossPOW algorithm is highly sensitive to the wind direction input. Therefore at least for the investigated period, the higher hit rate and a better performance is anticipated. It is also seen in Figure 6.4(c) that even for 5-minutes averaged dataset, the bandwidth of the wind speed inside the wind farm is as broad as 4 m/s. This automatically corresponds to significant production differences towards downstream, indicating the importance of fast, robust and as accurate as possible wake modelling once again. Despite the highly variable wind speed inside the wind farm, the PossPOW algorithm is seen to be in a good agreement with the dataset in terms of the 5-min averaged produced and predicted power on the wind farm scale.

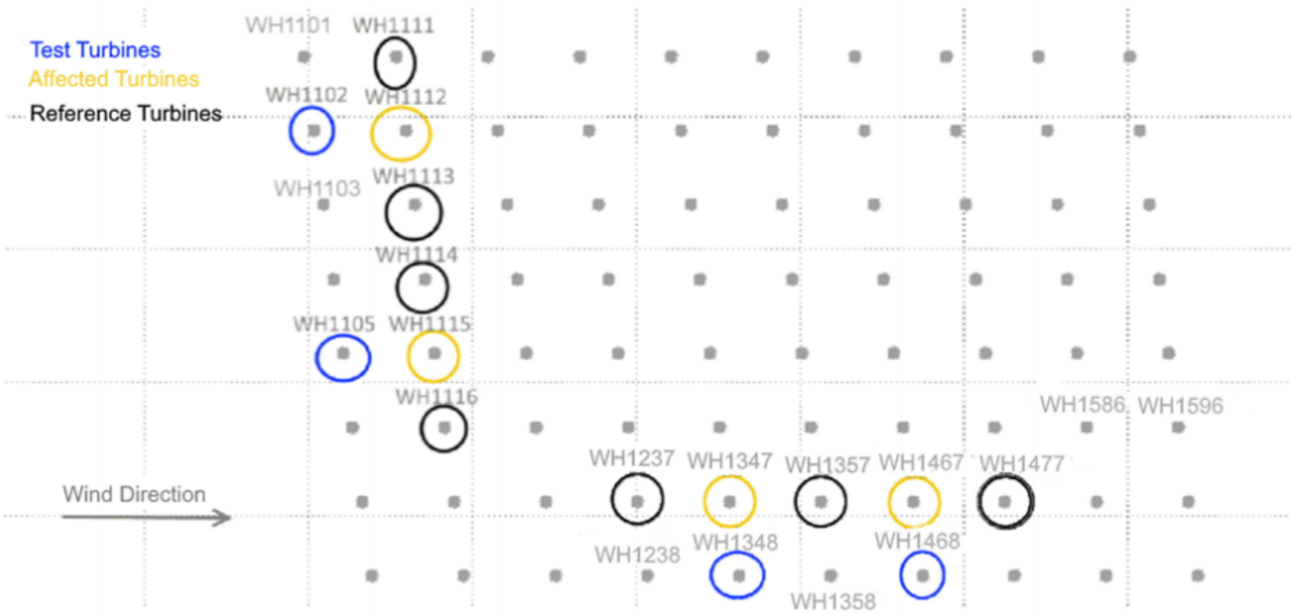

Figure 7.1: The down-regulation experiments for westerly winds in Horns Rev-I offshore wind farm. **Blue:** Curtailed turbines; **Yellow:** Turbines affected by the 'reduced' wake due to curtailment; **Black:** Reference Turbines to correct the 'reduced wake'

The experiments took place during the Spring of 2015 in the Horns Rev-I wind farm and they are basically aimed to validate the PossPOW algorithm, under restricted down-regulation conditions. The idea is to down-regulate two separate turbines (test turbines, WH1102 and WH1105) located on two of the inner rows west of the wind farm, as shown in Figure 7.1, page 70 in the thesis. In the downstream of the test turbines, the wake losses are reduced due to upstream curtailment, therefore the affected turbines see more wind than usual (turbines WH1112 and WH1115). The assumption is that the available power of the affected turbines is equal to the active power production of the closest neighbouring rows (reference turbines), for perpendicular westerly wind directions. In other words, the active power of the reference turbines with nominal wake deficit is assumed to be identical to the production capacity of the affected turbines. Therefore, the active powers of the turbines WH1111 – WH1113 and WH1114 – WH1116 are taken as the reference available powers for the turbines WH1112 and WH1115, respectively.

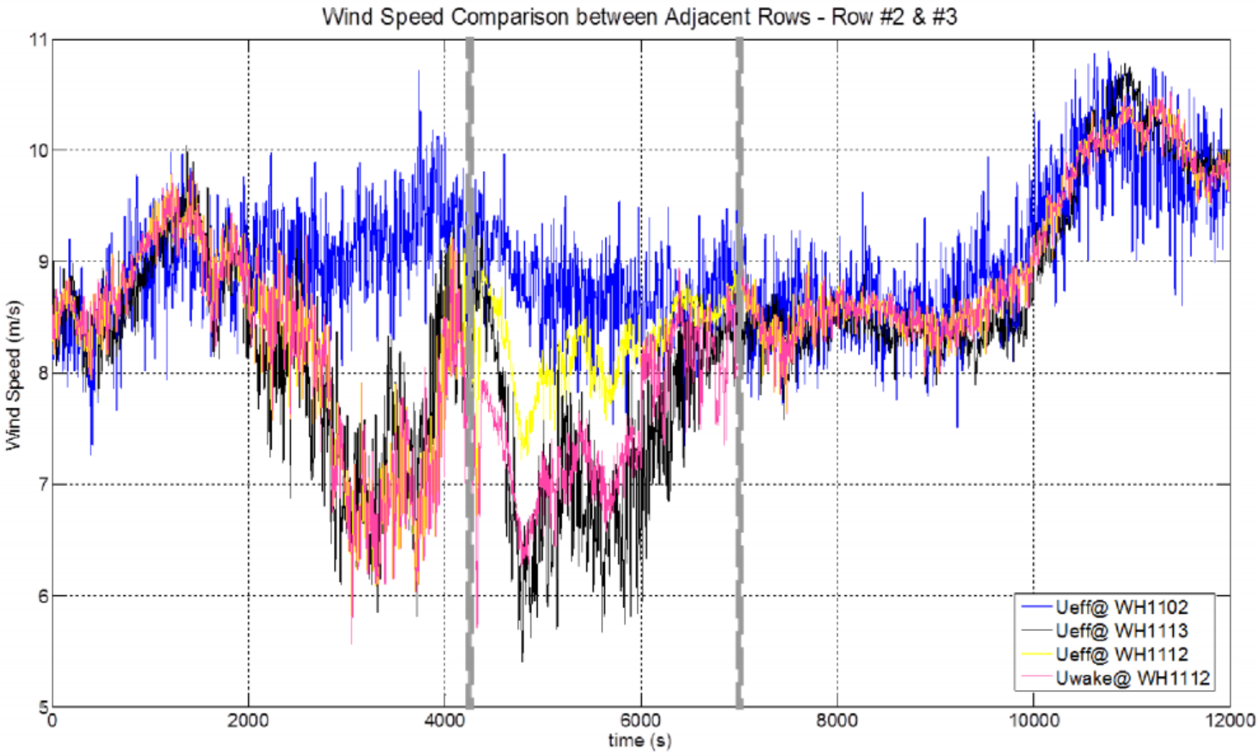

Figure 7.3: Comparison of the effective wind speed at the turbines: **WH1102** – upstream (test) turbine; **WH1113** – reference downstream turbine **WH1112** – affected downstream turbine and the **PossPOW** algorithm. Curtailment is activated between 4100–7000sec, Experiment #2

The first expectation from the experiments is to be able to clearly observe the reduced wake deficit due to upstream curtailment at the affected turbine, which is used to calculate the individual turbine level possible power SCADA signal. As mentioned earlier, the key challenge in the PossPOW project is to correct that reduced wake deficit and reproduce the wind speed profile at the reference turbine. For the experiment illustrated in Figure 7.3, page 74 in the thesis, the influence of down-regulation to the flow behind the turbine is most clearly seen. During the investigated period, where curtailment is activated between 4100 – 7000 seconds between the grey lines, two explicit wake occurrences are recorded. Along the full depth of the first wake which takes place just before the curtailment is activated, the wind speeds at the affected and the reference turbines downstream are seen to be in very good agreement. However during the curtailment in the second wake event, the affected turbine is exposed to significantly higher wind speeds. The PossPOW algorithm is applied to the whole dataset and seen to maintain a very good agreement with the reference turbine under both nominal and down-regulated operations.

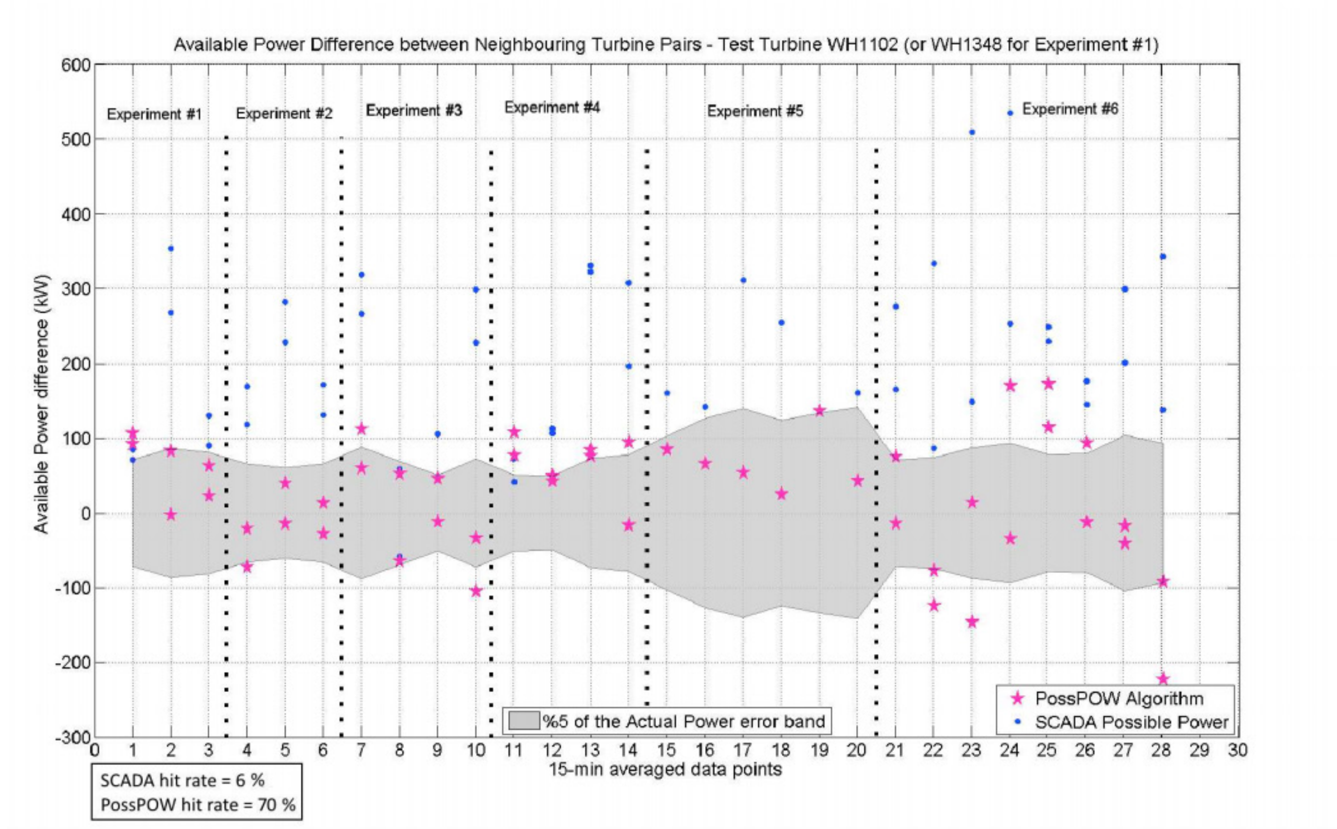

Figure 7.7: The comparison of SCADA Possible Power, and PossPOW algorithm results at turbine pairs WH1102 / WH1112 (or WH1348 / WH1347 for southerly winds in Experiment #1) with the adjacent rows, i.e. WH1101 / WH1111 and WH1103 / WH1113 for westerly winds; WH1238 / WH1237 and WH1358 / WH1357 for southerly winds) in Horns Rev-I experiments. $\pm 5\%$ of $\mathit{Actual\ Power} = \pm 5\%$ of $\mathit{Active\ Power}_{WH1102-WH1112}$

The PossPOW algorithm gives significantly better results compared to the aggregated SCADA possible power signals which is the standard industrial practice currently. Note that the 15-minutes averaged data points are collected using all the experiments with different inflow conditions (different upstream wind speed, turbulence intensity, etc.) which provides rather wide scope to evaluate the performance. The current practice is observed to be over-estimating the available power for most of the cases, where the PossPOW results are mostly within the ±5% error band with slight over and under-estimation together.

9. Publication and dissemination

Already early in the project, an external webpage with minimal information about the project was put up: http://www.posspow.dtu.dk/.

Giebel, Gregor; Göçmen Bozkurt, Tuhfe; Sørensen, Poul Ejnar; Poulsen, Niels Kjølstad; Runge Kristiansen, Jesper: "*PossPOW: Possible Power of Offshore Wind Power Plants*". Talk on the EWEA Annual Event 2013, 4-7 February, Vienna (AT).

T. Göçmen, G. Giebel, P.E. Sørensen, and M. Mirzaei: *PossPOW: Possible Power of Offshore Wind Power Plants.* Poster on the EWEA Offshore Conference in Frankfurt (DE), 19-21 November 2013

Tuhfe gave an oral presentation in the European Academy of Wind Energy (EAWE) 9th PhD Seminar on Wind Energy in Europe; Visby, Gotland Sweden between 18-20 September 2013.

"*Model Based Active Power Control of a Wind Turbine*", Mahmood Mirzaei, Mohsen Soltani, Niels K. Poulsen and Hans H. Niemann, American Control Conference, 2014, Portland, OR, United States

"Wind Speed Estimation and Parameterization of Wake Models for Downregulated Offshore Wind Farms", Tuhfe Göçmen Bozkurt, Gregor Giebel, Niels K. Poulsen and Mahmood Mirzaei. European Wind Energy Conference & Exhibition 2014, Barcelona, Spain

"Wind Speed Estimation and Parameterization of Wake Models for Downregulated Offshore Wind Farms", Tuhfe Göçmen Bozkurt, Gregor Giebel, Niels K. Poulsen and Mahmood Mirzaei.
in journal: Journal of Physics: Conference Series, vol: 524, issue: 1, 2014
Presented at: 5th International Conference on The Science of Making Torque from Wind 2014, 2014, Copenhagen

"*Estimation of the Possible Power of a Wind Farm*" Mirzaei, Mahmood ; Göçmen Bozkurt, Tuhfe ; Giebel, Gregor ; Sørensen, Poul Ejnar ; Poulsen, Niels Kjølstad. In journal: I F A C Workshop Series (ISSN: 1474-6670), vol: 19, pages: 6782-6787, 2014. Presented at: 19th World Congress of the International Federation of Automatic Control (IFAC 2014), 2014, Cape Town

There were two papers on the Wind Integration Workshop in Berlin:
"Estimation and Experimental Validation of the Available Power of a Downregulated Offshore Wind Power Plant" Gregor Giebel, Tuhfe Göçmen Bozkurt, Poul Sørensen, Mahmood Mirzaei, Niels K. Poulsen. 13th Wind Integration Workshop in Berlin, 11-13 November 2014. *(Oral Presentation in front of about 60 people from academia and industry / TSOs)*
"Effective Wind Speed Estimation and Real time Wake Model Re-calibration for Down-Regulated Turbines" Tuhfe Göçmen Bozkurt, Gregor Giebel, Pierre-Elouan Réthoré, Mahmood Mirzaei, Niels K. Poulsen. 13th Wind Integration Workshop in Berlin, 11-13 November 2014. *(Poster Presentation)*

Giebel, G., T. Göçmen Bozkurt, P.E. Sørensen, P.-E. Réthoré, N.K. Poulsen, M. Mirzaei, M.R. Skjelmose, J.R. Kristoffersen: *Experimental verification of a real-time power curve for down-regulated offshore wind power plants.* Poster on the EWEA Offshore Conference, Copenhagen (DK), 10-12 March 2015.

Göçmen Bozkurt, T., G. Giebel, P.E. Sørensen, P.-E. Réthoré, M. Mirzaei, N.K. Poulsen, M.R. Skjelmose, J.R. Kristoffersen: *Real-time available power estimation for offshore wind power plants*. Poster on the EWEA Offshore Conference, Copenhagen (DK), 10-12 March 2015.

Mirzaei, M., T. Göçmen Bozkurt, G. Giebel, P.E. Sørensen, N.K. Poulsen: "*Turbine Control Strategies for Wind Farm Power Optimization*". Presented at the American Control Conference, Chicago (US), 1-3 July 2015.

Giebel, G., T. Göçmen Bozkurt, et al.: "*Verified available power estimation of offshore wind farms*". Poster on the EWEA Annual Event 2015, Paris (FR), 17-20 November 2015.

A public dissemination workshop was held for one afternoon at Risø on 29 October 2015 in the framework of the VES Workshops. Together with the PhD enrolled in PossPOW, Tuhfe Göçmen; Knud Johansen (Energinet.dk), Lars H. Hansen (DONG Energy Wind Power), Mads Rajczyk Skjelmose (Vattenfall Wind DK A/S) and Jayachandra N. Sakamuri (DTU Wind Energy) were invited as speakers.

Tuhfe Göçmen submitted her thesis on 14 December 2015 and successfully defended on 9 March 2016:

Göçmen, T. 2016, *Possible Power Estimation of Down-Regulated Offshore Wind Power Plants*. Ph.D. Thesis, Technical University of Denmark.

Göçmen, T, van der Laan, P, Réthoré, P-E, Pena Diaz, A, Larsen, GC & Ott, S 2016, *"Wind turbine wake models developed at the Technical University of Denmark: A review"* Renewable & Sustainable Energy Reviews, vol 60, pp. 752–769.

T. Göçmen, G. Giebel, M.R. Skjelmose, J.R. Kristoffersen, M. Støttrup: *PossPOW: Possible Power of Offshore Wind Power Plants*. Invited talk on the Workshop „Präqualifikation von Windkraftanlagen für Minutenreserveleistung", organised by German TSOs, Berlin, 10 February 2016 [held in German]