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# Offshore wind farms: losses and turbulence in wakes

## Modeling and validation

P.J. Eecen

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Presented at the Wake Workshop, June 8-9 2011, Gotland University, Sweden

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# Abstract

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# Offshore wind farms: losses and turbulence in wakes. Modeling and validation

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## FarmFlow: model description

ECN developed a software tool to calculate the wind turbine wake effects in offshore wind farms: the reduction of the wind speed and the added turbulence behind the wind turbines. The ECN tool is called 'FarmFlow' and is an effective compromise between models based on empirical formula and very complex and time consuming flow solvers. The validated FarmFlow model accurately predicts the wake losses and turbulence levels in offshore wind farms. In various validation exercises the accuracy of the FarmFlow software has been proven.

FarmFlow is based on a three-dimensional CFD model that solves the parabolized Navier-Stokes equations. Turbulence is modeled by means of the k-ε turbulence model. Since the wake model is three-dimensional, it is applicable in the atmospheric boundary layer. The basic flow field parameters (wind rose) and wind turbine properties (cp and ct curves) are used as input. Due to the parabolization of the Navier-Stokes equations, axial pressure gradients in the wakes are neglected. This is a plausible assumption at some distance away from the wind turbines and allows for a fast numerical solution. However, in the near wake region pressure gradients are eminent, since in this region the wake expands and the flow decelerates. Therefore FarmFlow uses a hybrid method that models the wake expansion and flow deceleration directly through prescribed axial pressure gradients in the near wake.

The wake of a wind turbine is divided in a near wake, an intermediate wake, and a far wake. The near wake is the region where the wake expands as a result of the increasing pressure in flow direction. The near wake ends a few rotor diameters downstream the rotor plane, where the maximum velocity deficit at the centerline is reached and the pressure equals the free stream value. The near wake region is dominated by inviscid processes. In the intermediate wake region, the turbulent mixing is concentrated in an annular shaped shear layer, while at the centerline the velocity remains constant. The far-wake region is the region that is best modeled by the k-ε turbulence model. ECN has improved the turbulence modeling in the near wake region.

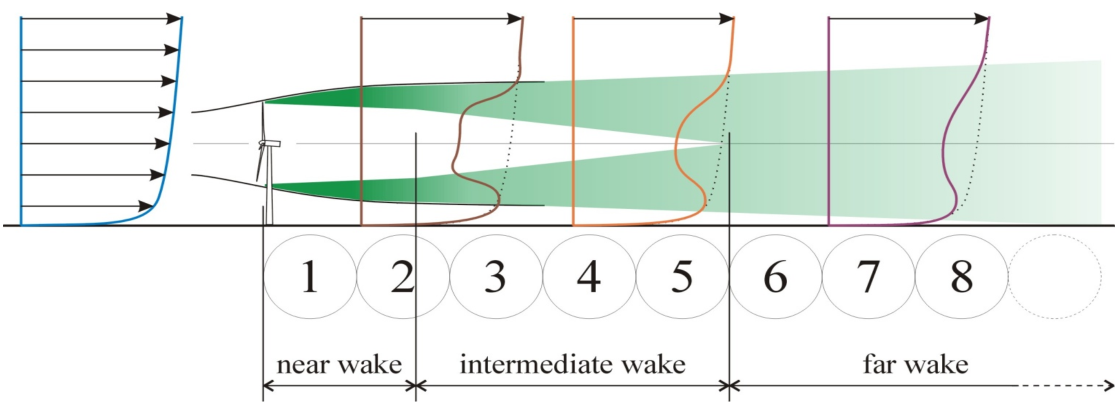


Figure 1: The division of the wake in near, intermediate and far wake regions.

## FarmFlow: comparison with measured wake losses

The tool FarmFlow is the result of many years of development of wake models dedicated to off-shore farm modeling (since 1993). Over the years, the underlying model has been validated against a varyity of measurements. Here the comparison of the FarmFlow calculations with measurements from Horns Rev wind farm are presented. The comparison was part of the European Upwind project [1], and the data used here have been obtained from publications [2]. An earlier example of comparison is [3, 4].

In fig.2 the relative power levels at the various wind turbines in the Horns Rev offshore wind farm are plotted averaged over the sector from 255-285 degrees. It is clear that the FarmFlow model is capable to model correctly the losses in the offshore wind farm. In fig.3, the computational domain is indicated. The left figure is a snapshot of the flow field just behind the turbine, the colors indicate wind speed. Clearly visible is the wake directly behind the turbine (blue). The yellow area indicated the wake of other upwind turbines. Note that a large domain above the wind farm is calculated. This ensures that the exhaust of energy above the wind farm due to mixing with the wakes is included in the model.

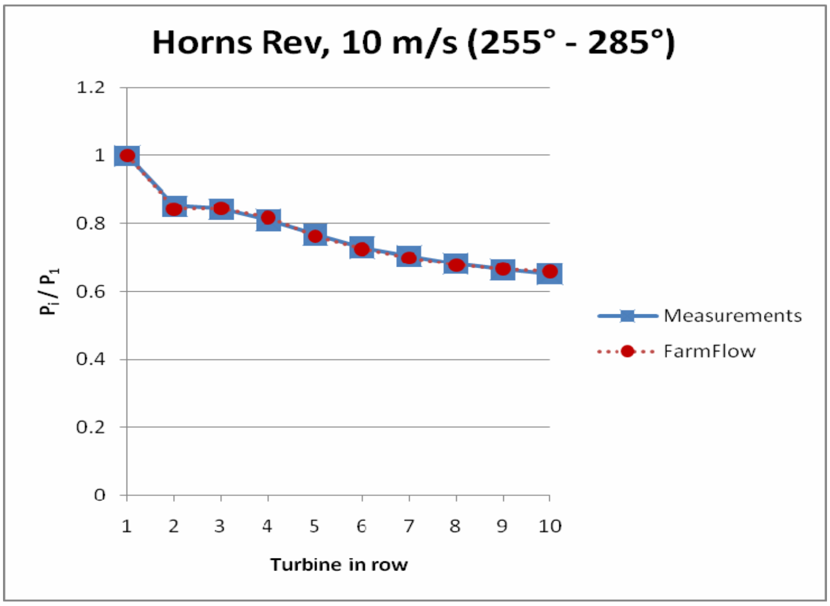


Figure 2. The power levels relative to the first turbine in the row is plotted for the sector of 255-285°.

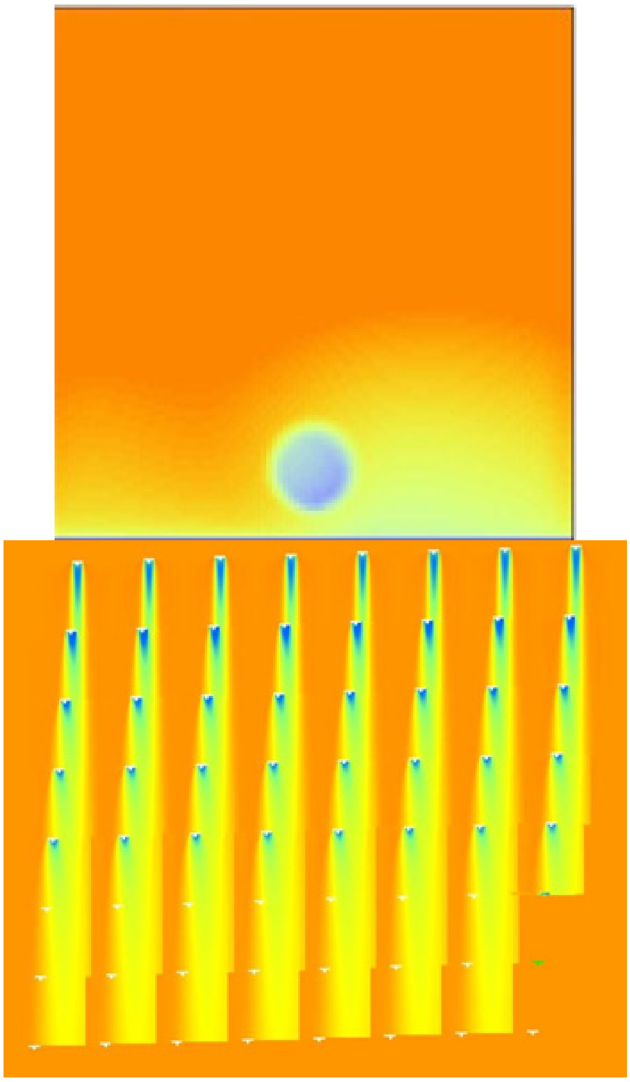

Figure 3. A visualization of the computational domain. Colors indicate wind speed. Left is indicated a snapshot of the calculation presented on the right.

## FarmFlow: comparison with measured turbulence levels

FarmFlow is capable of calculating the farm losses as well as the turbulence levels within off-shore wind farms at the same time: it is an integral part of the underlying CFD model. For the comparison of turbulence levels calculated with FarmFlow with measurements from offshore wind farms, the Dutch offshore wind farm Egmond aan Zee (OWEZ) has been used [5]. In this wind farm, a measurement and evaluation program (MEP) has been executed. Part of the MEP is the installation and operation of a meteo mast, which was installed in the summer of 2005. The turbines were erected in the last part of 2006. Some data are available from internet [5] and a description of the metmast is reported in [6].

For all three heights at the meteo mast a wind speed and a wind direction has been defined for which the mast influences are minimised [6]. The wind speed and wind direction measurements at 70m height (hubheight of the turbines) are used in the analysis.

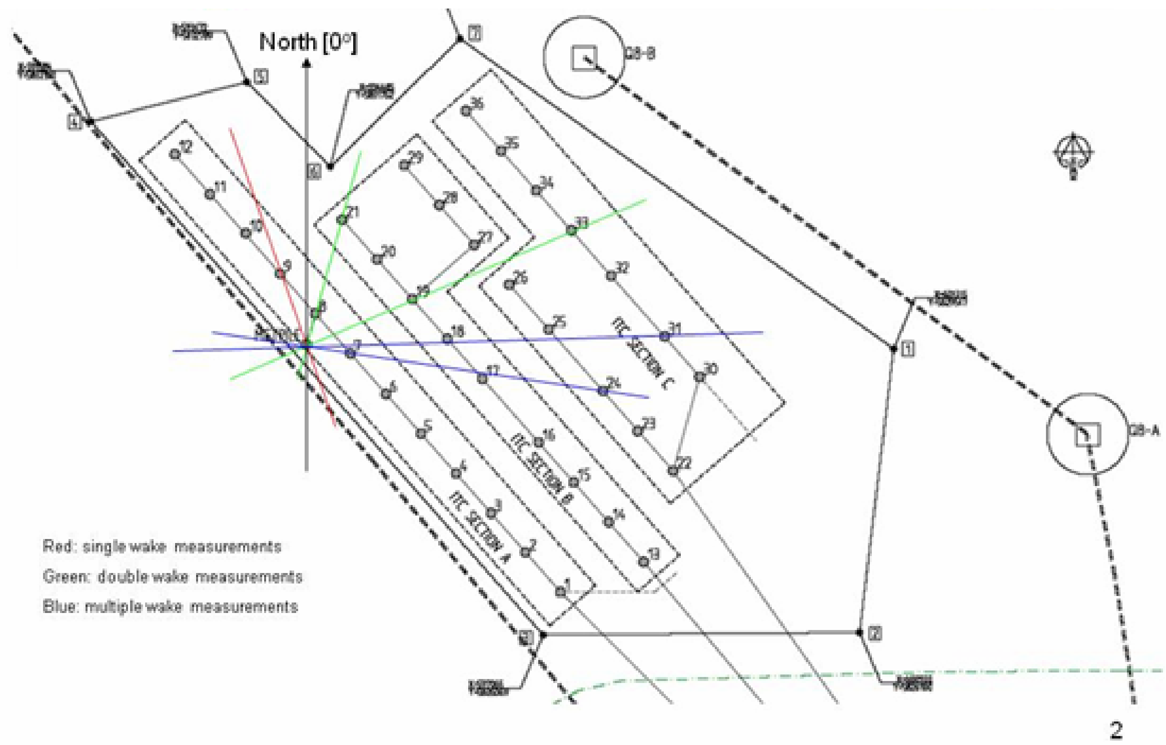


Figure 3: The lay-out of the Offshore Wind farm Egmond aan Zee (OWEZ) with wake indication. The wind farm consists of Vestas V90 turbines.

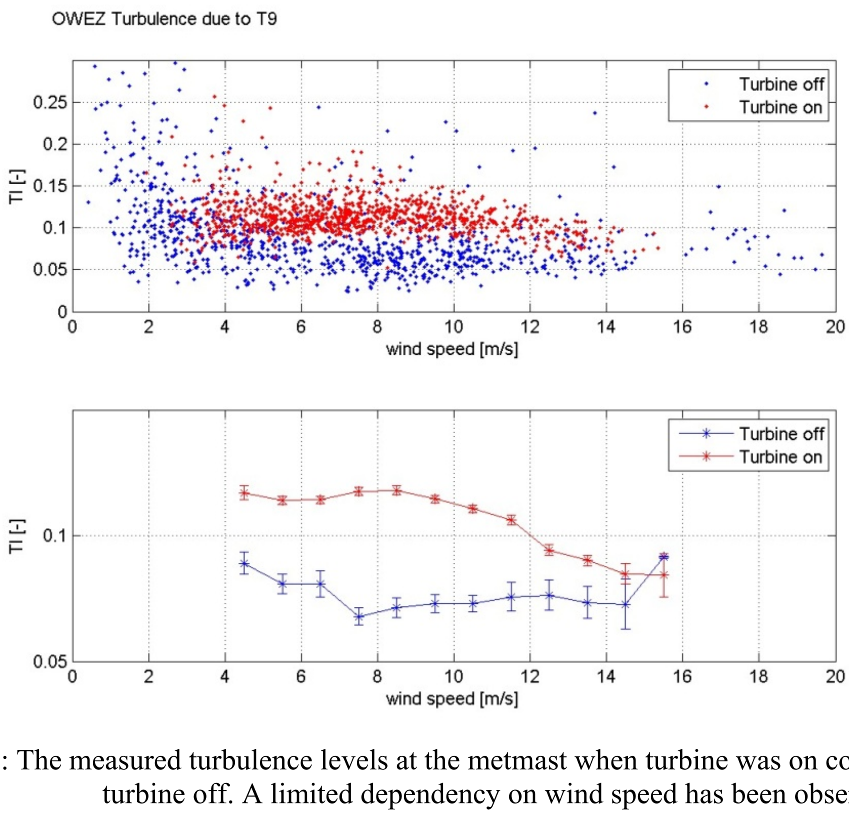


Figure 4: The measured turbulence levels at the metmast when turbine was on compared to turbine off. A limited dependency on wind speed has been observed.

The analysis of turbulence level in the offshore wind farm has been performed as follows. The wind speed and wind direction is measured at the mast. When the wind direction is from the turbine to the mast, the mast is in the wake of the turbine. These measurements are used and the dataset is divided by measurements where the turbine was operational and when the turbine was either not yet installed or not operational. The difference in turbulence level is then attributed to the wake of the turbine.
To investigate to what extend the turbulence intensity depends on the wind speed, turbine T9 is considered. This turbine is located at a distance of 10.2D (916m) from the meteo mast and at direction of 340°. A wind direction window of 5° is chosen. With respect to the meteo mast, T9 produces a single wake when T9 is active, see fig.4.
The measured turbulence at the metmast is plotted in two groups; one (blue) where the turbine was operational and the other (red) where the turbine was not operational. For the latter, remember that there was a year of measurements before the turbines were installed. The data are shown in fig.4, and a clear difference is observed between the two turbulence levels. It is observed that the added turbulence level is slightly depending on wind speed. That means that the uncertainty due to lack of measurement of the ambient wind speed to the analysis of turbulence is limited.

Fig.5 shows the measured turbulence levels at the metmast for various distances to the turbines (measured in rotor diameters). The upper plot indicates the measured turbulence intensity, the lower plot indicates the added turbulence due to the presence of the wake. The analysis has been performed for various wind speed intervals indicated by color.

A more detailed analysis is performed and shown in Fig.6. Here the wind directions around 102° are used. In that sector turbine T7 is located at a distance of 6.0D (543m) from the metmast and turbine T17 is located at a distance of 24.2D (2174m). Data have been selected where the wind direction is between 92 degrees and 112 degrees and wind speeds above 4m/s. Fig.6 shows the binned values where a bin size of 2.5 degrees is chosen. The uncertainty bars are the standard deviation of the mean bin values. The different colours stand for different combinations of turbines being on and off.

The comparison with results from FarmFlow show that the software tool is capable to accurately predict the turbulence level in offshore wind farms.

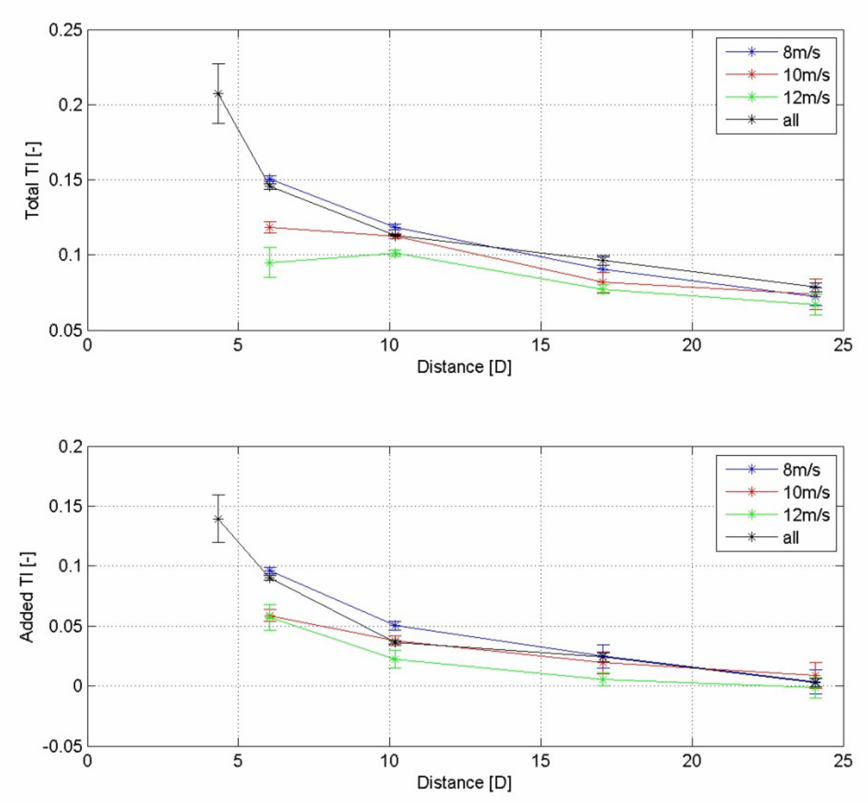


Figure 5: The measured turbulence levels at the metmast for various distances to the turbines. The upper plot indicates the measured turbulence intensity, the lower plot indicates the added turbulence due to the presence of the wake. The colors indicate wind speed intervals.

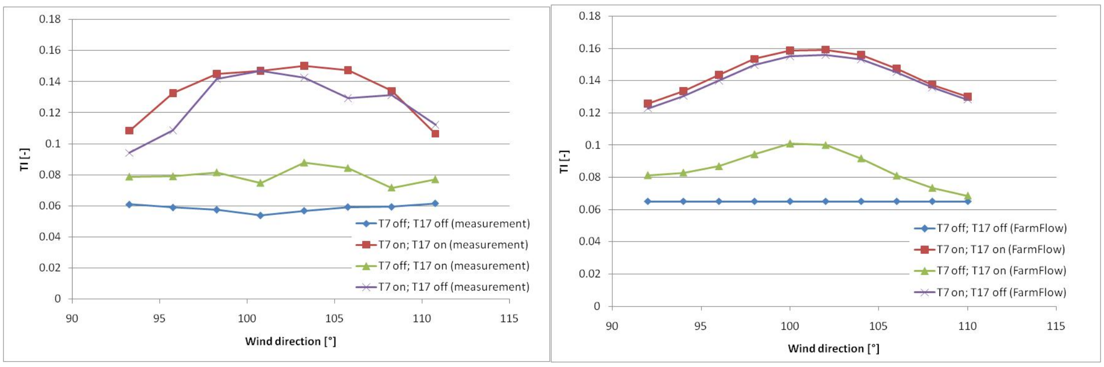


Figure 6: The measured turbulence levels at the metmast for the sector 90-110 degrees, where T7 and T17 are either operational or not. Left are measurements, right are results from FarmFlow.

# CONCLUSIONS

ECN developed a software tool to calculate the wind turbine wake effects in offshore wind farms: the reduction of the wind speed and the added turbulence behind the wind turbines. The ECN tool is called 'FarmFlow' and is an effective compromise between models based on empirical formula and very complex and time consuming flow solvers. The validated FarmFlow model accurately predicts the wake losses and turbulence levels in offshore wind farms.
In the paper it is shown that the wake losses are accurately predicted. The emphasis in this paper is the added turbulence in offshore wind farms. It has been shown that turbulence levels are increase to large distances behind the turbines and that FarmFlow can accurately predict the added turbulence due to the wakes in offshore wind farms.

# REFERENCES


[1] UPWIND Design limits and solutions for very large wind turbines, March 2011, http://www.ewea.org/fileadmin/ewea_documents/documents/upwind/21895_UpWind_Report_low_web.pdf.

[2] R.J. Barthelmie, S.T. Frandsen, K. Hansen, J.G. Schepers, K. Rados, W. Schlez, A. Neubert, L.E. Jensen, S. Neckelmann, Modeling the impact of wakes on power output at Nysted and Horns Rev, EWEC 2009

[3] L.A.H. Machielse, P.J. Eecen, H. Korterink, S.P. van der Pijl, J.G. Schepers, ECN test farm measurements for validation of wake models, ECN-M--07-044, EWEC2007

[4] P.J. Eecen, E.T.G. Bot, Improvements to the ECN wind farm optimisation software FarmFlow" ECN-M--10-055, EWEC 2010

[5] www.noordzeewind.nl

[6] P.J. Eecen, L.A.H. Machielse, A.P.W.M. Curvers, Meteorological Measurements OWEZ, Half year reports, ECN-E--07-073 to ECN-E--07-076
(also available from www.noordzeewind.nl)

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# Wind farm calculation and optimization with FarmFlow

Dr. P.J. Eecen

8th June 2011

Wake Conference – Visby

www.ecn.nl

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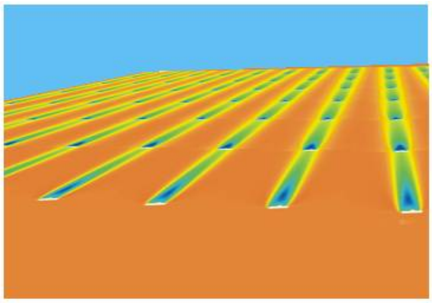
## Outline



- Wind farm layout and wind farm losses
- Introduction to FarmFlow
  - The theory and model description
- Validation FarmFlow – comparison with data
  - Production Losses
  - Added Turbulence

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## Wake effects on a turbine in a wind farm

- Lower wind speed in wake: <u>Energy loss</u>
- Larger shear: <u>Higher mechanical loads</u> (Partial wake!)
- Higher turbulence level: <u>Higher mechanical loads</u>
- Different turbulent length scale:
  - <u>Higher mechanical loads</u>
- Coherence of turbulence differs:
  - <u>Higher mechanical loads</u>

**Wake losses are significant – typically 5 % upto 40%**
**Added turbulence intensity – from 6-8% to 20-25%**

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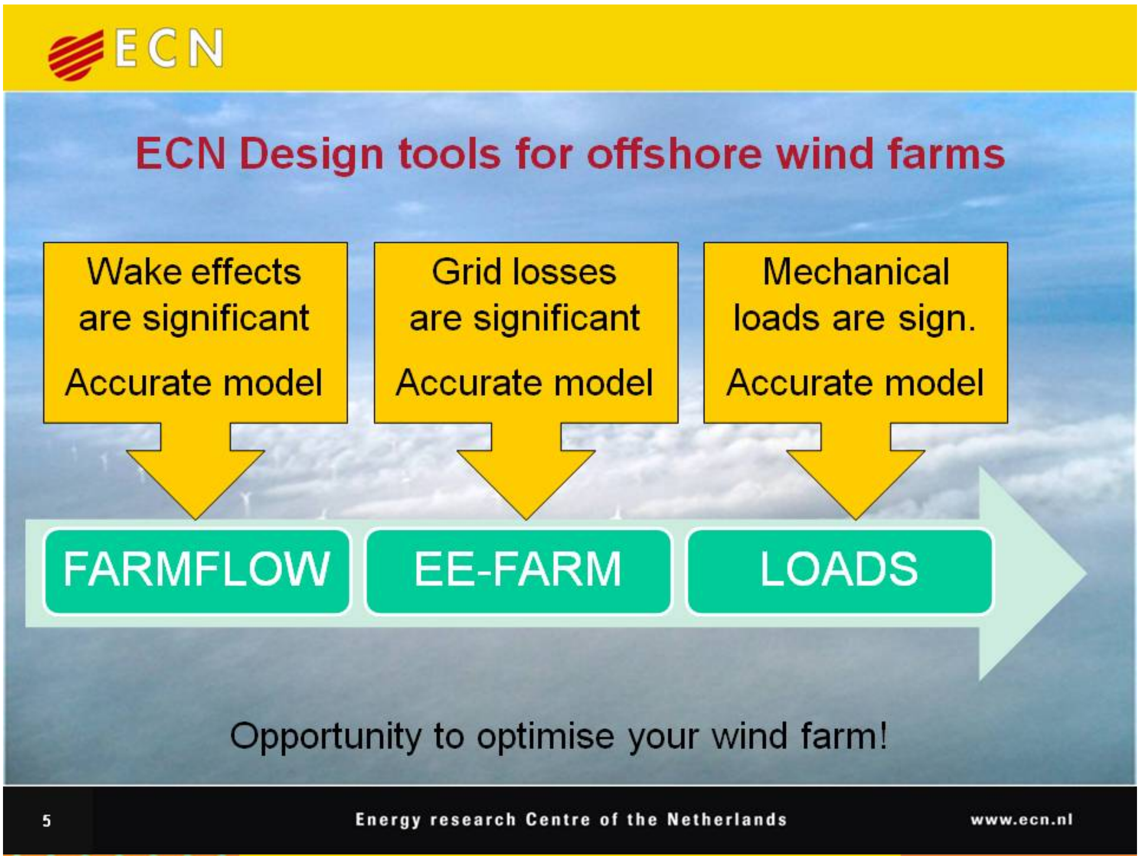
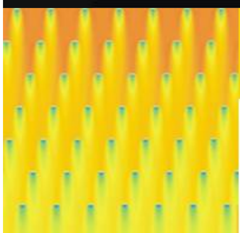
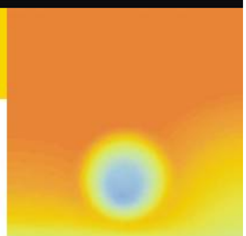


## The ECN model FARMFLOW



- Easy to use program to accurately calculate aerodynamic wind farm effects in Offshore Wind Farms
- Calculates
  - losses and added turbulence due to wakes
  - annual energy production (AEP)
- The model is based on UPMWAKE (1) / WAKEFARM
  Modified by ECN since 1993
  Since 2000 dedicated to offshore wind farms

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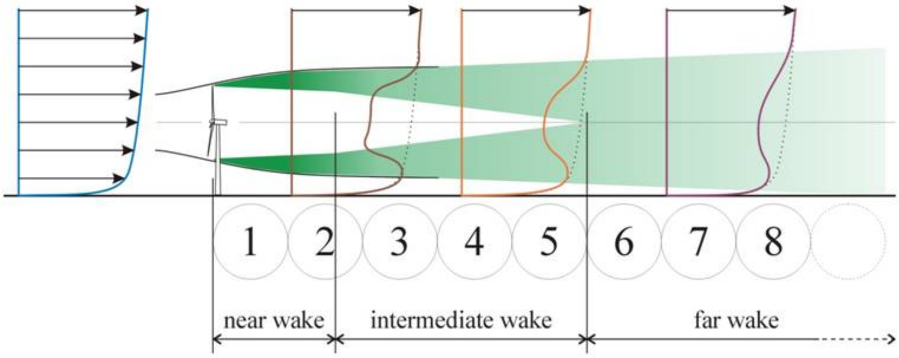
## The Theory and the Model description

### FARMFLOW

- Solves the Parabolized Navier-Stokes equation
- Permeable disc for the turbines
- k-ε turbulence model




(1) (Crespo et al. 1988)

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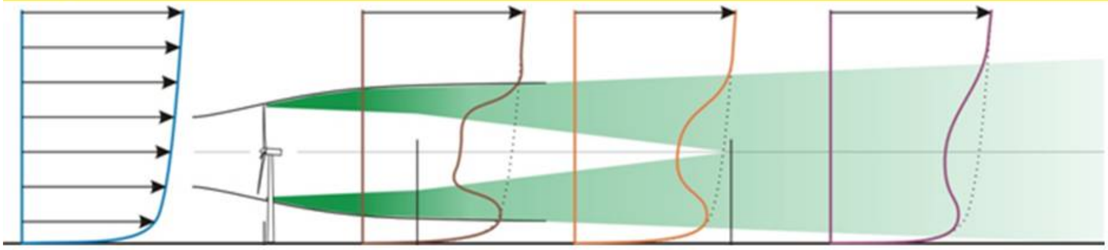
## FARMFLOW Advanced Model Properties



- Gradual wake expansion and flow deceleration enforced by prescribed axial pressure gradients
- Pressure gradients obtained from free vortex wake method
  - No prescribed wake defect → wake interaction fully modeled
- Adjusted k-ε turbulence model parameters in near wake, based on measurements

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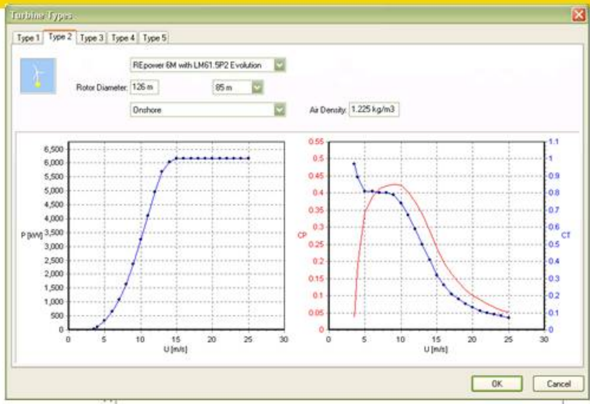
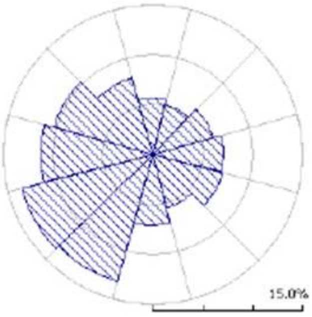
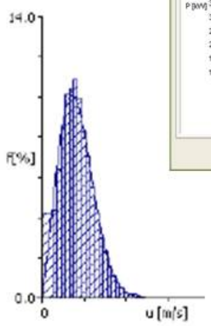
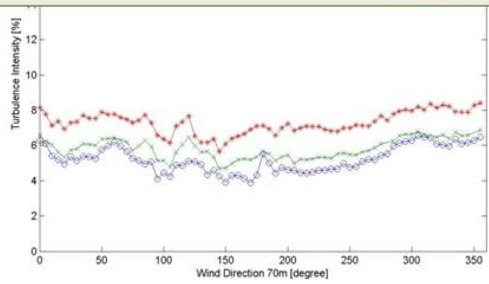
## ECN Required input



- Power curve and thrust curve are required (from brochure)




- Wind rose and Turbulence rose required

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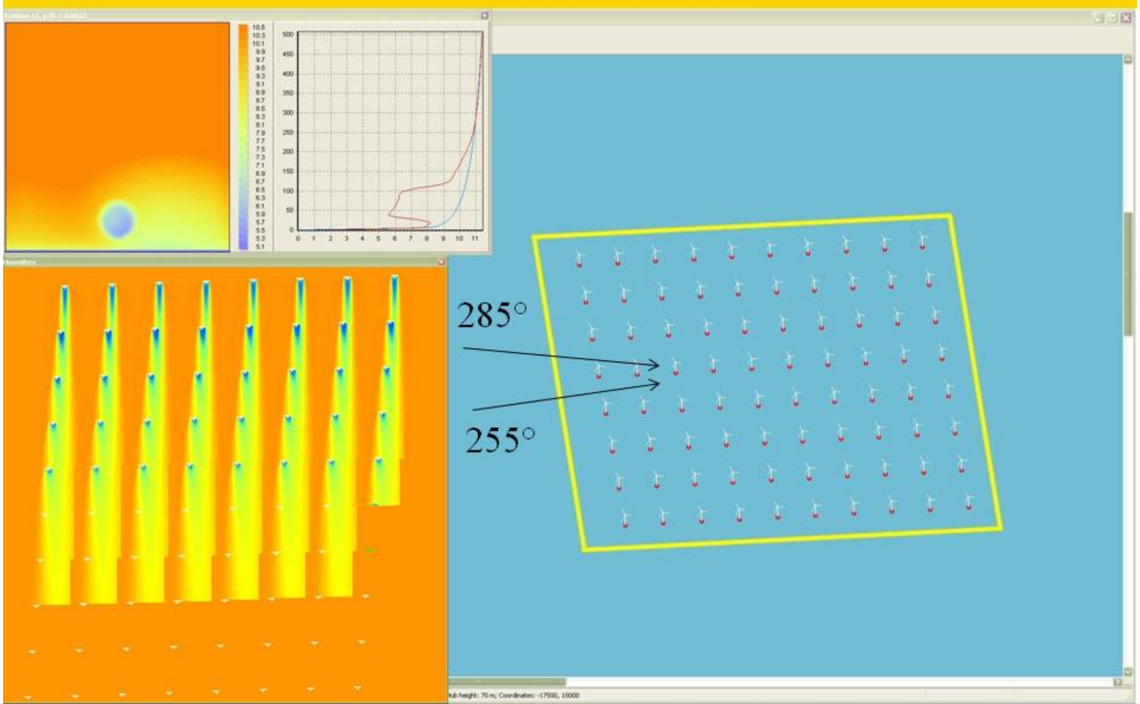
## ECN Validation and Comparison – Horns Rev

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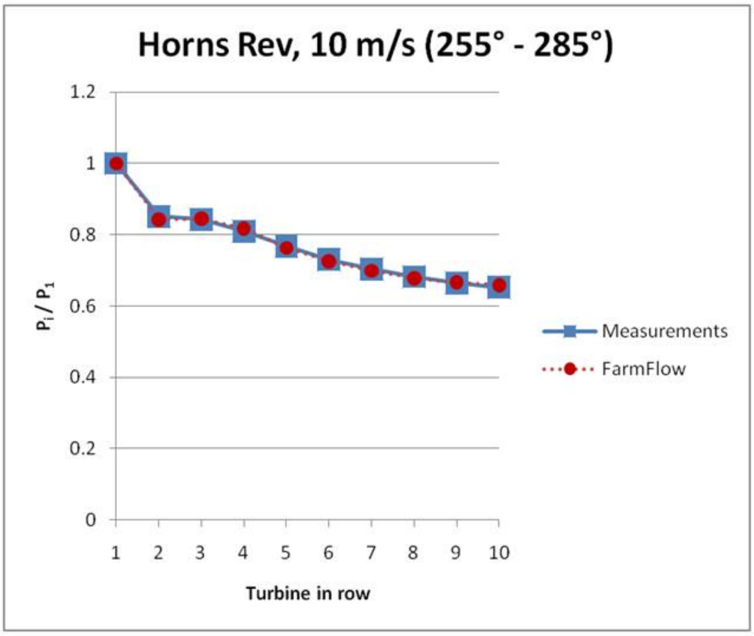
# Validation and Comparison



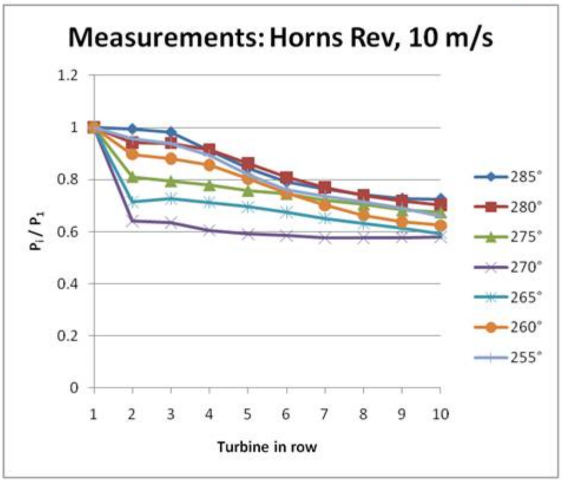

- Horns-Rev Wind Farm measurements
- Averaged power of $i^{th}$ turbine in row divided by $1^{st}$ turbine in row at 10m/s for the sector from 255° to 285°.

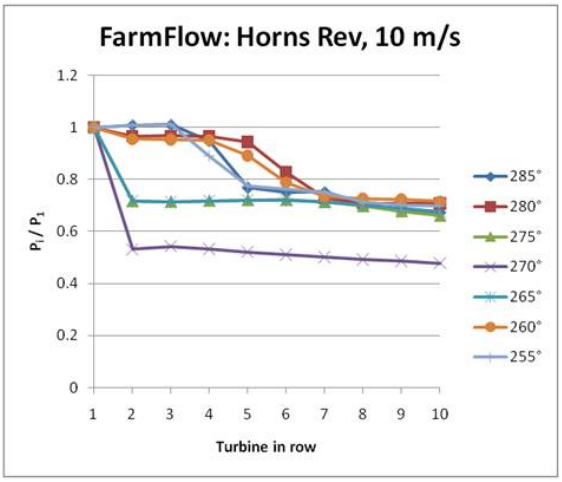
- Data from: R.J. Barthelmie, S.T. Frandsen, K. Hansen, J.G. Schepers, K. Rados, W. Schlez, A. Neubert, L.E. Jensen, S. Neckelmann, Modeling the impact of wakes on power output at Nysted and Horns Rev, *EWEC 2009 (The data are obtained from this publication)*





# Validation and Comparison with Data




- Differences explained by wind direction changes.
  To cross the wind farm at 10m/s takes 500 seconds!
- R.J. Barthelmie et al, Modeling the impact of wakes on power output at Nysted and Horns Rev, *EWEC 2009 (The data are obtained from this publication)*

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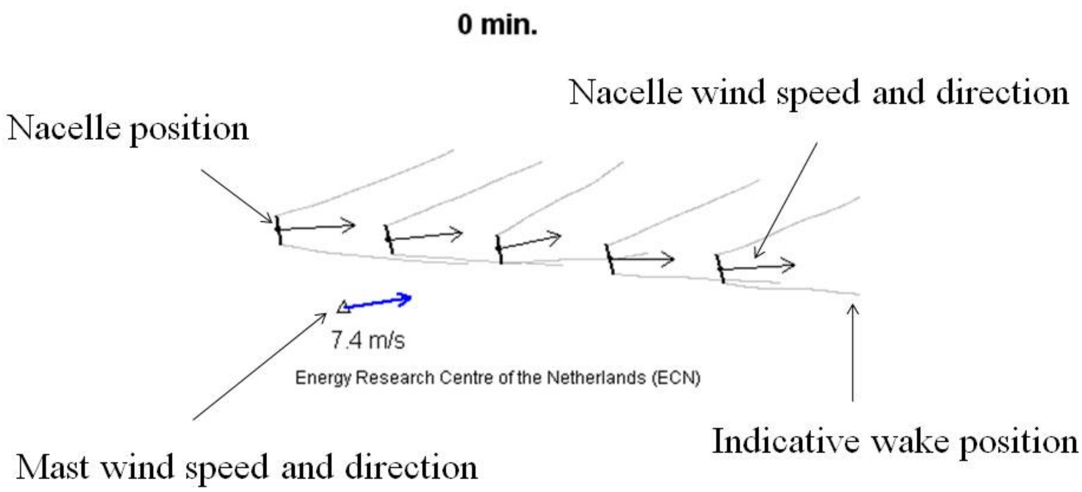
## Measured data EWTW




Five multi MW research wind turbines at ECN windturbine test site Wieringermeer

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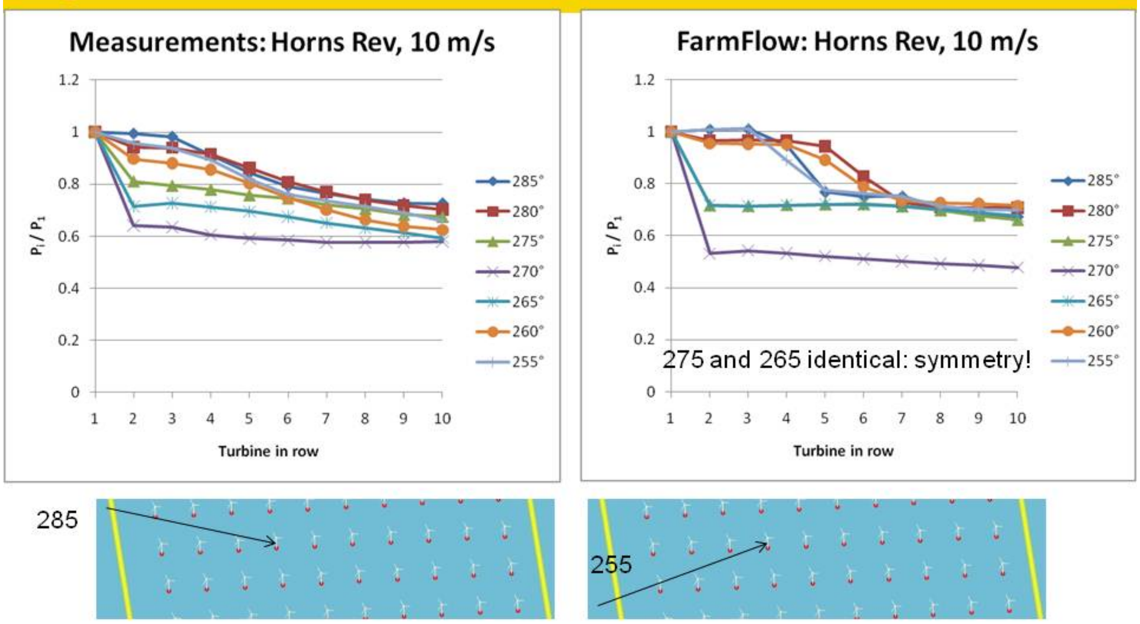


- R.J. Barthelmie et al, Modeling the impact of wakes on power output at Nysted and Horns Rev, *EWEC 2009* *(The data are obtained from this publication)*

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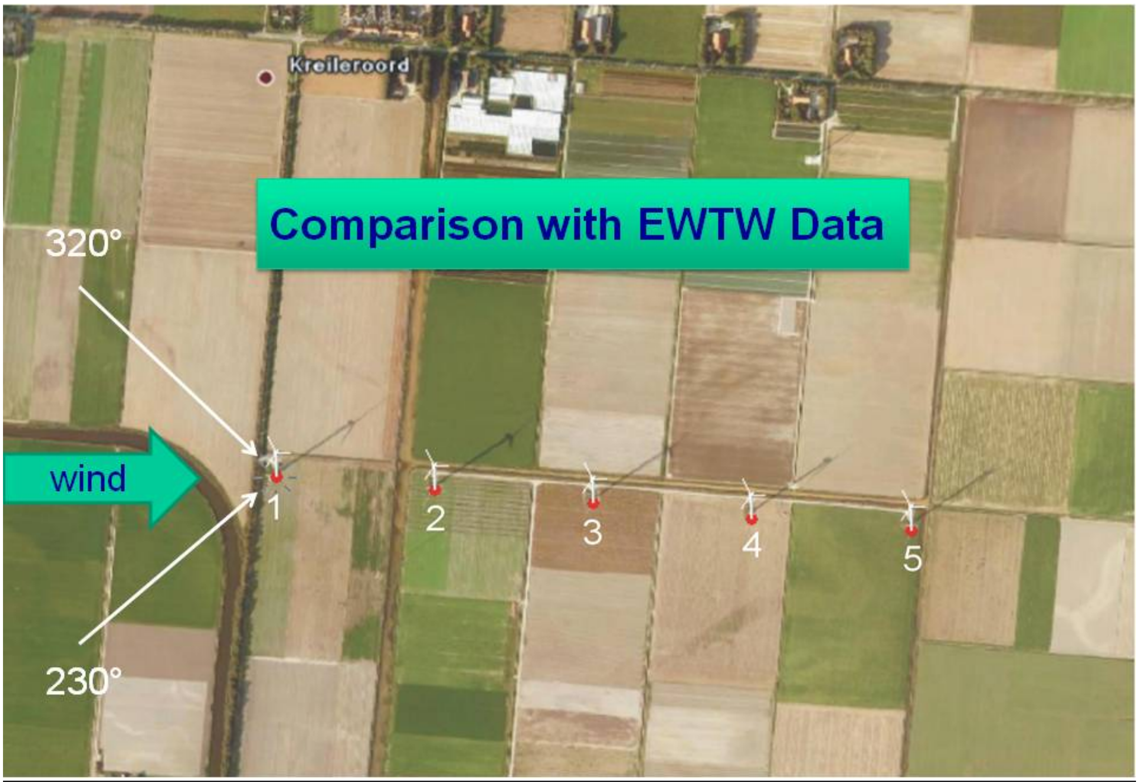


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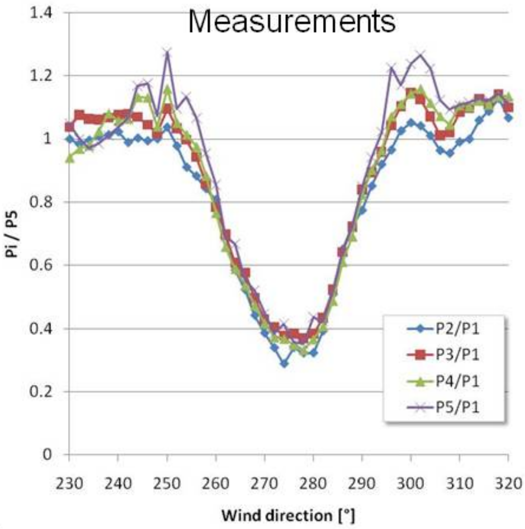
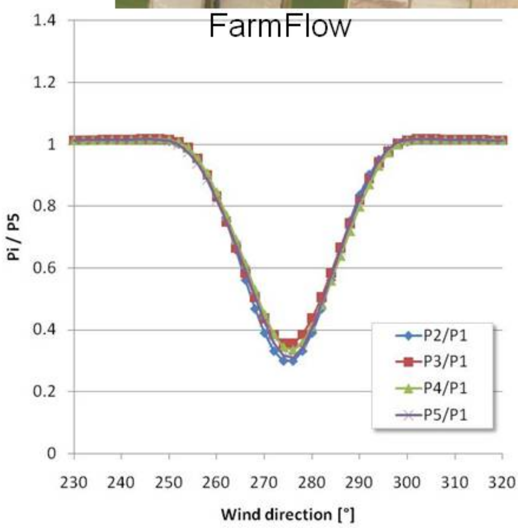
## Comparison
## Power Ti / Power T5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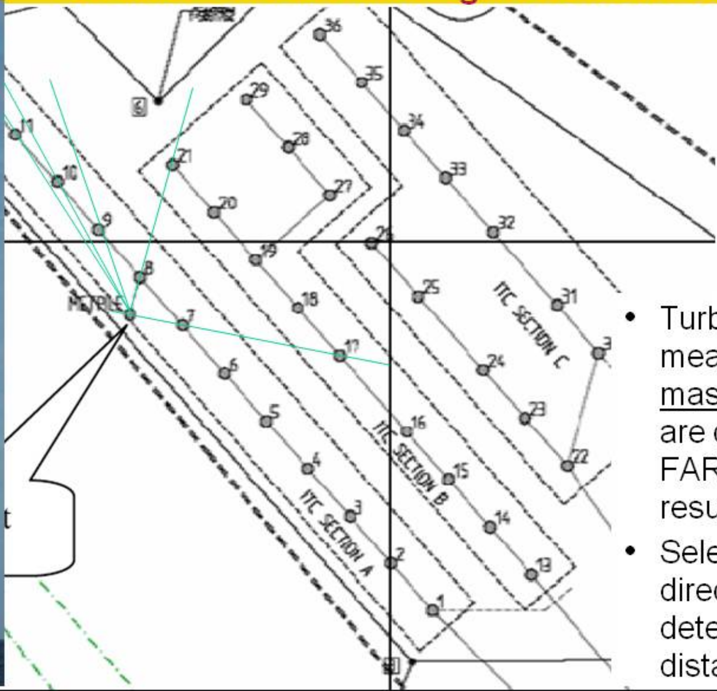
## Turbulence Analysis
## Offshore Wind Farm Egmond aan Zee (OWEZ)




| Turbine | Distance (D) |
|---|---|
| 8 | 4.3 |
| 7 | 6.0 |
| 9 | 10.2 |
| 10 | 17.1 |
| 11 | 24.1 |

- Turbulence measurements at mast from OWEZ are compared to FARMFLOW results.
- Selection of direction determines distance

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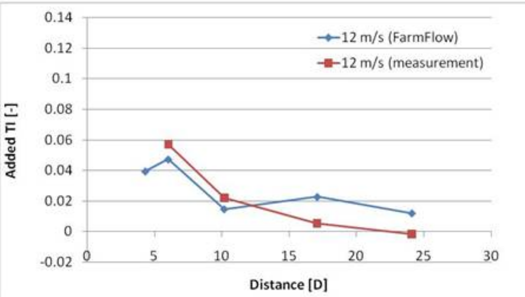
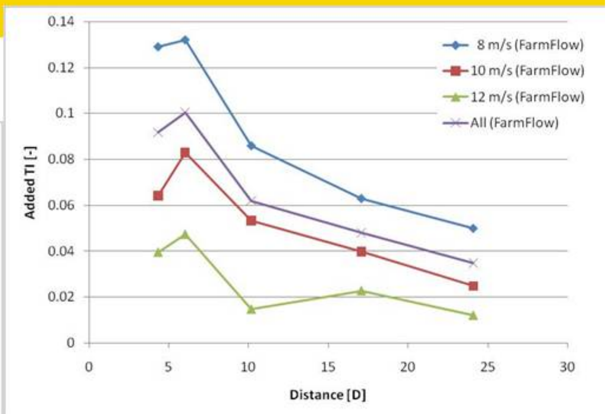
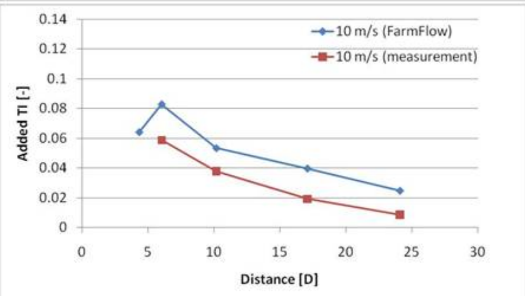
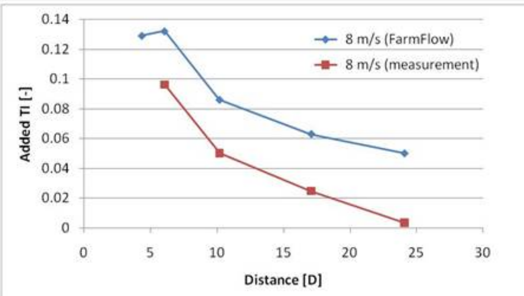
## Turbulence Analysis

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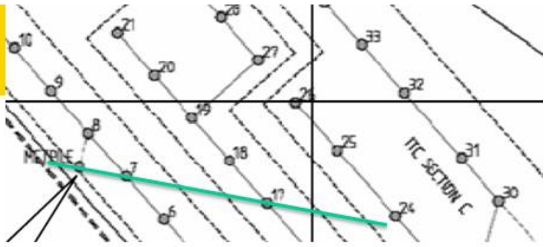
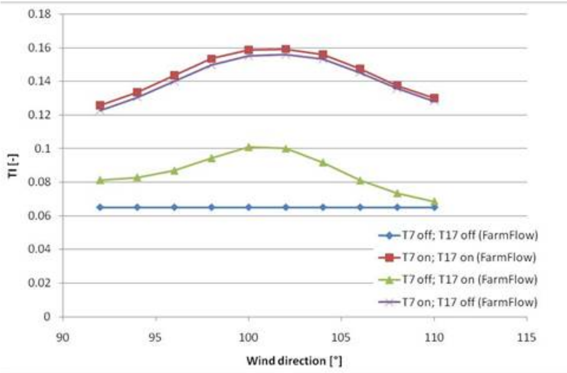
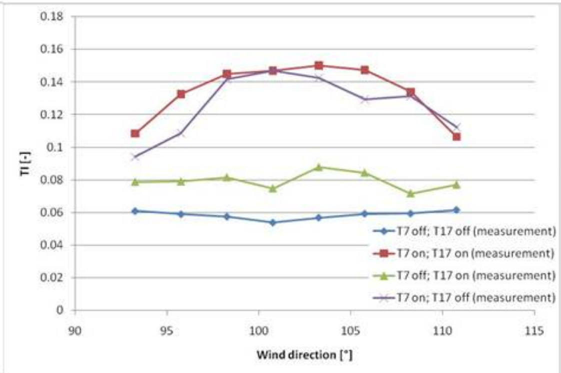
## Turbulence Intensities




- Measured at hub height at meteo mast when turbines are on/off

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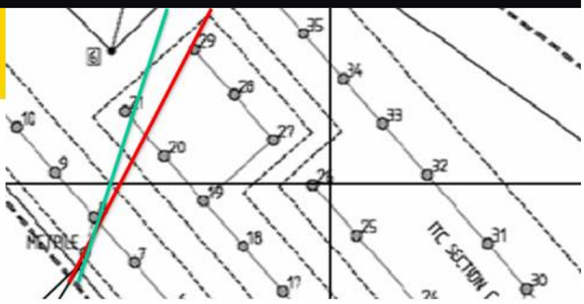
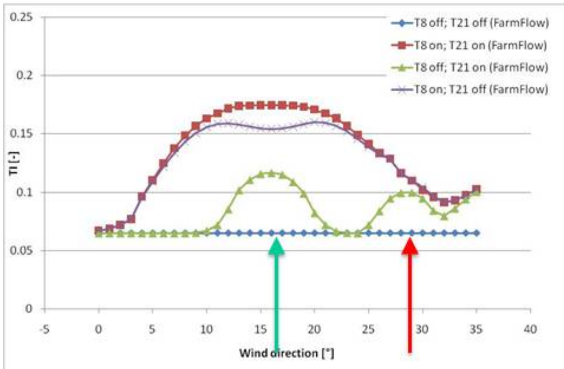
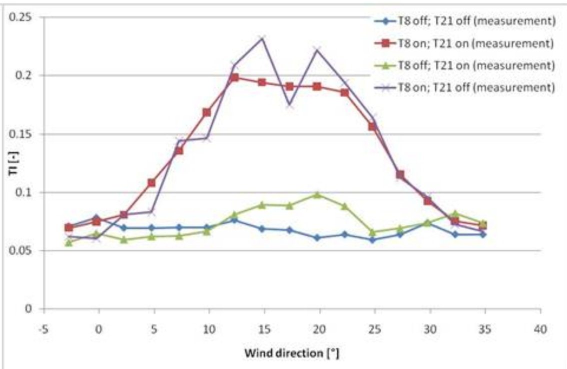
## Turbulence Intensities




- Measured at hub height at meteo mast when turbines are on/off

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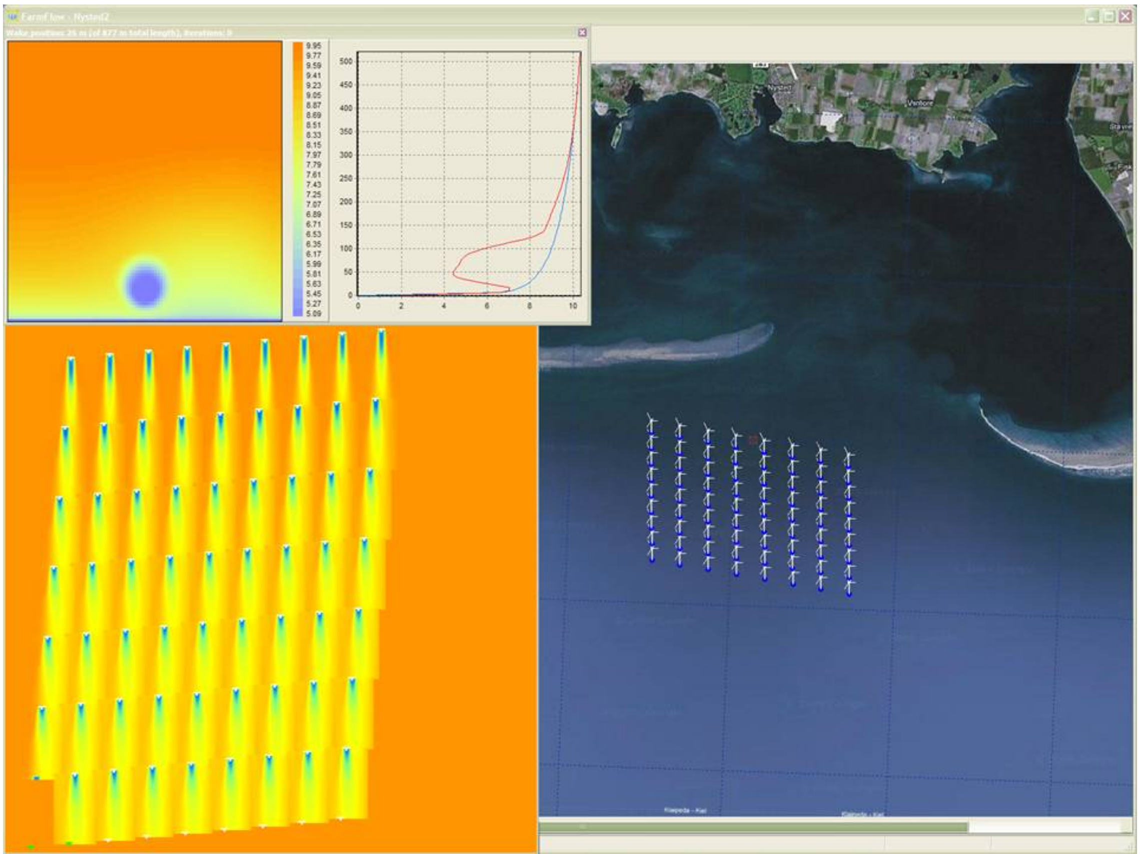

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## Summary and Conclusions

- It is important to accurately calculate aerodynamic and electrical losses in large offshore wind farms
- FarmFlow is accurate and validated tools to calculate
  - Wake losses
  - Added turbulence
  - Cost of Energy
- Today presented: validation cases agains power and turbulence measurements in offshore wind farms

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