Westerduinweg 3
1755 LE Petten
P.O. Box 15
1755 ZG Petten
The Netherlands

www.tno.nl

T +31 88 866 50 65

TNO report

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Wind farm yield estimation with DOWA

Date	9 March 2020
Author(s)	E.T.G. Bot
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Summary

The publicly available Dutch Offshore Wind Atlas (DOWA) has been created within the DOWA-project, that has been executed by the project partners KNMI, Whiffle and 'ECN part of TNO', with support from the Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call). The DOWA provides accurate wind field information up to heights of 600 m for a full 10 year period, aiming specifically at the wind energy industry. The DOWA is validated against satellite measurements, meteorological masts and LiDAR measurements.

This report describes an additional validation study, comparing observed yields from the Offshore Wind farm Egmond aan Zee (OWEZ) with simulated production yields. The simulations are performed with TNO's wind farm design tool FarmFlow, using time series of both DOWA and KNW wind atlases. For both wind field sources the results show very good correlations between the simulated and observed power productions per wind turbine. After calibration with a measure-correlate-predict method (MCP), both wind atlases perform similar. Without calibration, DOWA benefits from a more accurate prediction of the vertical wind shear, resulting in better predictions of offshore wind farm yields in the North Sea.

Contents

1 Introduction

In addition to WP6.2, "Comparison of AEP and power curve predictions from LES runs with turbine parameterizations", wind farm power predictions with DOWA input have been compared with measurements. In this work package, the Offshore Wind farm Egmond aan Zee (OWEZ) is considered as "pilot site" for the uncertainty assessment. NoordzeeWind has provided times series of OWEZ production data for the period 2008-2010. ECN part of TNO has simulated the production of OWEZ with ECNs wind farm design tool FarmFlow [1] using time series of wind data from both DOWA and KNW for comparison with the production data.

The OWEZ wind farm consists of 36 Vestas V90 3MW wind turbines with a total capacity of 108 MW. The wind farm is located 10 to 18 km off the coasts of Egmond aan Zee, with a size of 27 km^2. Numbering and location of the wind turbines are shown in Figure 1-1.

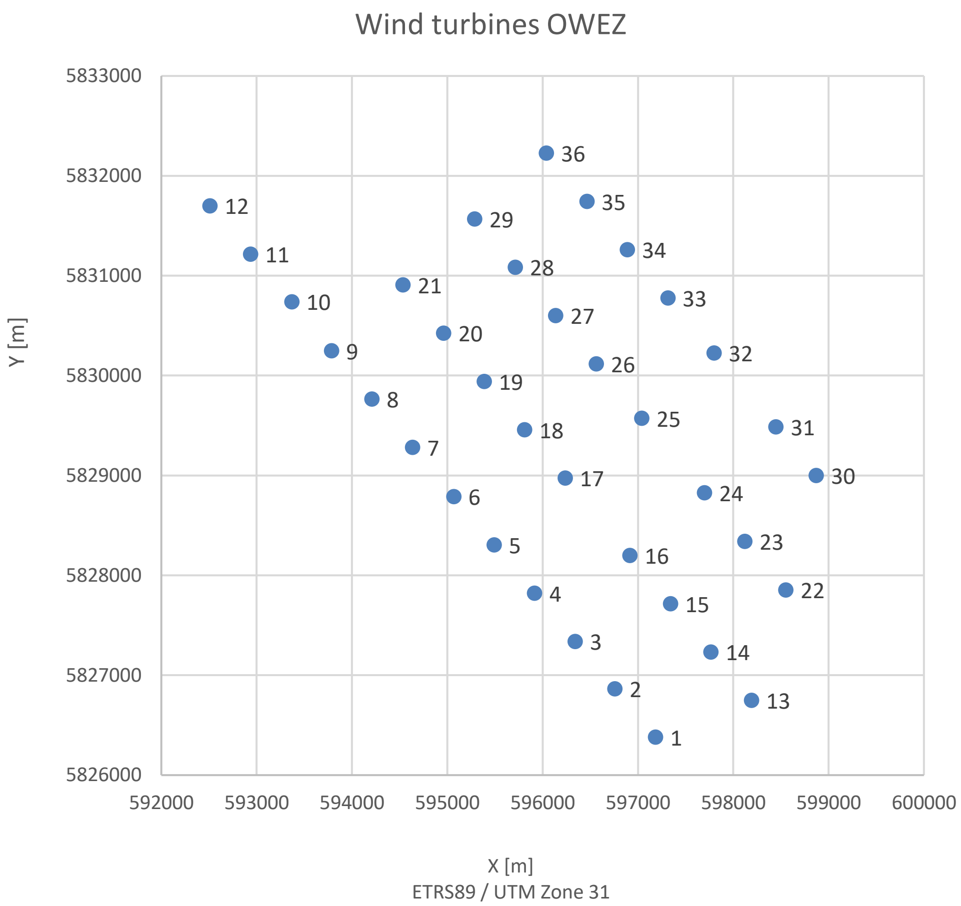

Figure 1-1 Numbering and locations of the Vestas V90 3MW wind turbines of OWEZ

2 Methodology

For the first three years of DOWA, 2008, 2009 and 2010, TNO has received time series of production data of the OWEZ wind turbines from NoordzeeWind. Due to low availability of data for the years 2008 and 2009, only 2010 has been used for this study. The production data of individual turbines in 2010 has an availability of 94.6% on average, with the lowest availability of 78.9% for turbine 14. After data filtering out periods with low availability (< 31/36), a time series of production data remained with an average availability of 93.6% for the selected year 2010.

DOWA contains time series of hourly wind data (wind direction, wind speed, pressure, temperature, humidity). The time series of OWEZ production data are 10 minute averages. Because DOWA time series contain hourly wind data, the simulated production data using DOWA time series as input will also be hourly averaged data. To enable direct comparison between simulated and measured production per wind turbine, the 10 minute averaged observations of the energy production per turbine are transformed to time series of hourly averages first.

Part of the input to the wind farm design tool FarmFlow is the standard power curve which is based on measurements following the procedure specified in IEC 61400-12 [2]. This means that the values in the power curve are mean values based on 10-minute periods from contiguous measured data and normalized to the reference air density for standard atmosphere (1.225 kg/m^3). Part of the output of FarmFlow are the so-called ‘power matrix’ files for each turbine. The power matrix files contain the net power curves including wake losses for 72 wind directions. These net power curves are based on the measured power curve and include effects of varying wind speed during 10-minute periods.

The hourly information in DOWA are not average value for the full hour, but rather 10 minute average data. For every hour in the DOWA time series, productions from the power matrix files are interpolated for each turbine. The power matrix files are first post-processed to simulate the average wind speed and wind direction variation by averaging over a continuous normal probability distribution. The standard deviations for these probability distributions have been determined from measurements at the met mast IJmuiden Ver. The standard deviation of the 10 minute and 60 minute change in average wind speed at IJmuiden Ver is 0.6 m/s and 1.1 m/s respectively. Since the power curve already contains the variation during 10 minutes, only the extra variation per hour needs to be taken into account. The standard deviation of the extra wind speed variation per hour is $\sigma_{\mathrm{WS}} = \sqrt{1.1^2 - 0.6^2} = 0.92$ m/s. The standard deviation of the 60 minute change in average wind direction at IJmuiden Ver is $\sigma_{\mathrm{WD}} = 9.6°$. Because no wind direction variation is included in the power matrix files, the full variation of the wind direction per hour needs to be taken into account.

The power curves in the power matrix files are valid for the reference air density for standard atmosphere. Therefore, the DOWA wind speeds are first normalized to standard atmosphere before the powers are read from the power matrix files:

$$U_{\mathrm{ref}} = U_{\mathrm{DOWA}} \left(\frac{\rho_{\mathrm{DOWA}}}{\rho_{\mathrm{ref}}}\right)^{1/3}, \tag{1}$$

where ρ_{ref} is the air density for standard atmosphere (1.225 kg/m^3), U_{DOWA} and ρ_{DOWA} are the actual wind speeds and air densities according to DOWA, and U_{ref} are the normalized wind speeds.

3 Wind turbine data input

The OWEZ wind farm consists of 36 Vestas V90 3MW wind turbines. These wind turbines have a rotor diameter of 90 m, a hub height of 70 m above means sea level and a capacity of 3 MW. The standard power curve of the Vestas V90 3MW is shown in Figure 3-1 together with the thrust curve. The thrust is the drag force that is responsible for the wake behind the turbine.

Figure 3-1 Standard power and thrust curve of the Vestas V90 3MW wind turbine

The standard power curve is based on measurements following the procedure specified in IEC 61400-12. This means that the values in the power curve are mean values based on 10-minute periods from contiguous measured data and normalized to the reference air density for standard atmosphere (1.225 kg/m^3).

4 Wind data input

DOWA contains time series on a 2.5 by 2.5 km grid spacing with 20 m height spacing around hub height. Around the OWEZ wind farm a quadrangle has been defined with its vortices coinciding with grid locations of DOWA, where virtual met masts are placed in FarmFlow, see Figure 4-1. At these virtual met masts, time series from DOWA for the year 2010 at 60, 80 and 100 m have been imported including wind direction, wind speed, pressure, temperature and relative humidity. From the last three variables, the air densities have been determined.

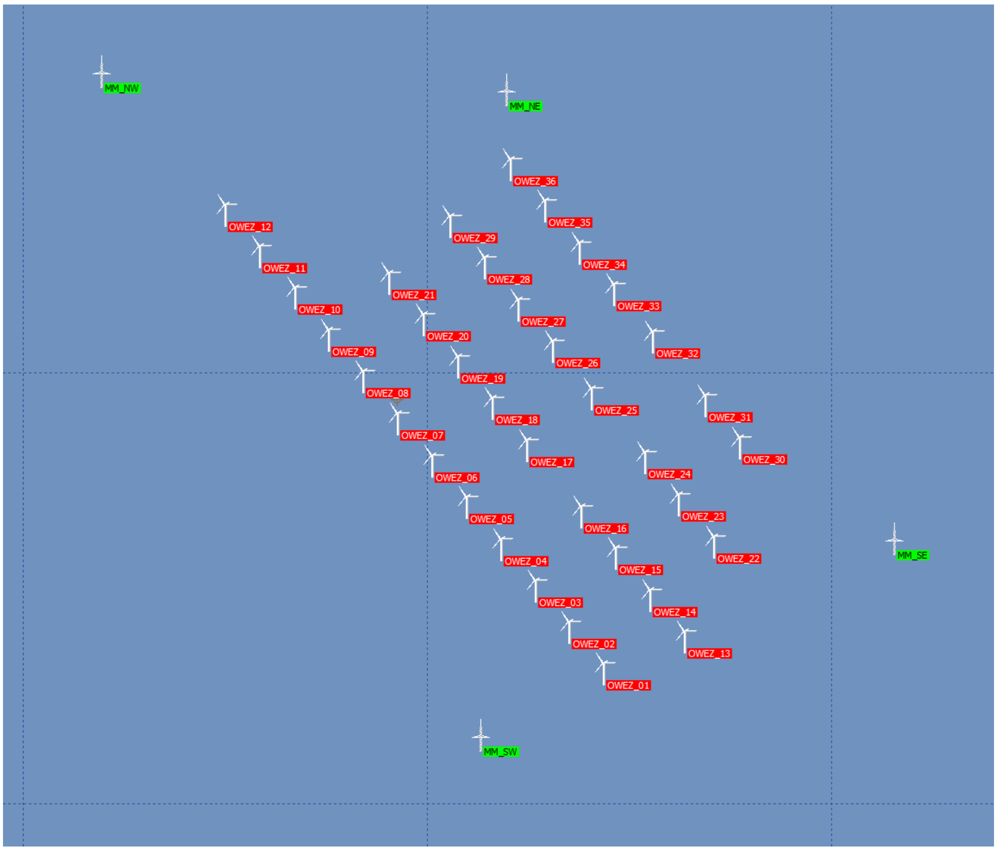

Figure 4-1 FarmFlow model of the OWEZ wind farm containing 36 wind turbines surrounded by four virtual met masts positioned on DOWA grid locations

The wind speed time series have been normalized to the reference air density for standard atmosphere, matching the conditions of the standard power curve of the Vestas V90 wind turbine (see section 3). The normalization of the wind speed is according to the equation (1).

The normalized wind speed time series at the four locations and three heights are transformed to 12 wind roses, containing the frequency distribution of the wind direction over twelve sectors, and per sector the Weibull parameters of the wind speed distribution.

Finally, the 12 wind roses have been interpolated per sector towards the locations and hub height of the 36 wind turbines.

For comparison between results with DOWA and KNW wind data input, the same approach has been repeated with KNW wind data.

5 Results

Figure 5-1 shows a comparison of the measured and simulated hourly power productions per turbine for OWEZ in 2010. The simulations show a small underestimation around the cut-in wind speed (3.5 m/s) and a small overestimation around the nominal wind speed (14 m/s). This suggests that the average variation of the wind speed per hour has been higher than the simulated variation with the continuous normal distribution with a standard deviation of 0.92 m/s.

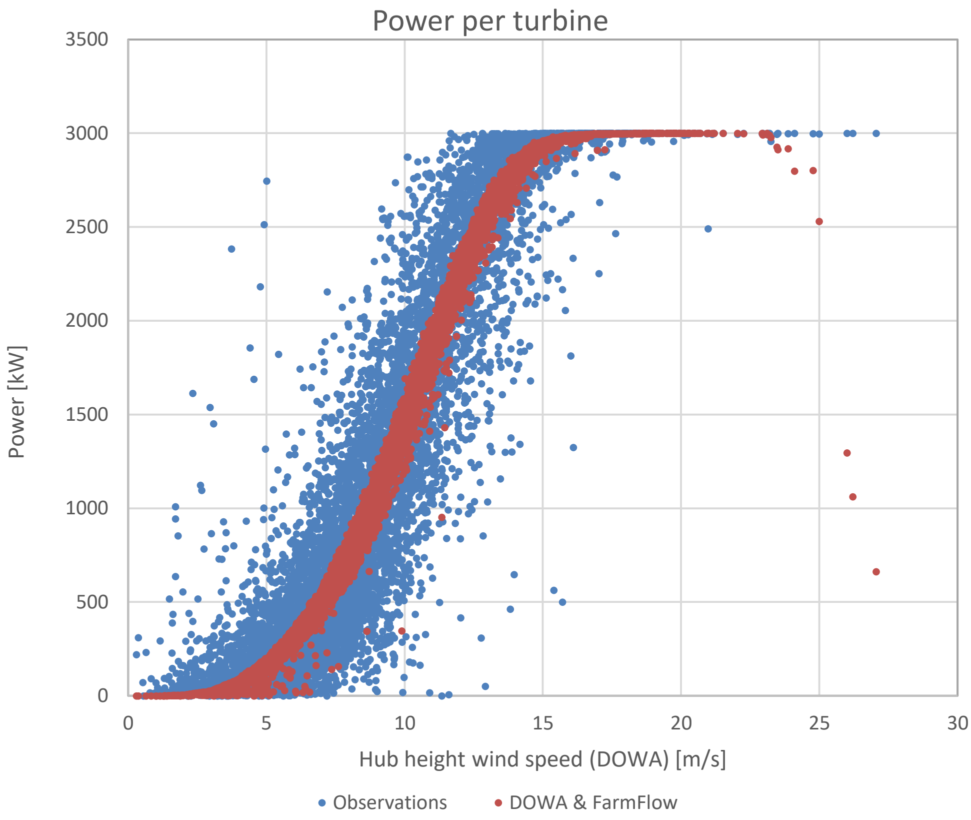

Figure 5-1 Comparison of the measured and simulated hourly power productions per turbine in OWEZ

In contrast with the FarmFlow simulations, the measurements show no reduced power around the cut-out wind speed of 25 m/s. In the FarmFlow results, the reduction starts around 23 m/s due to the wind speed variation per hour. It is unknown why the measurements don't show any power reductions due to cut-out, although the measurements show 4.5 hours of operation above the cut-out wind speed.

In Figure 5-2 the average of the measured and simulated power per turbine is plotted as a function of the DOWA wind speed. The graph contains vertical error bars at the observed values that represent the 95% confidence intervals, and a histogram of the data count per wind speed bin. Apart from the wind speeds around cut-in, cut-out and nominal wind speed, the results from the FarmFlow calculations with DOWA wind are always within the 95% confidence intervals.

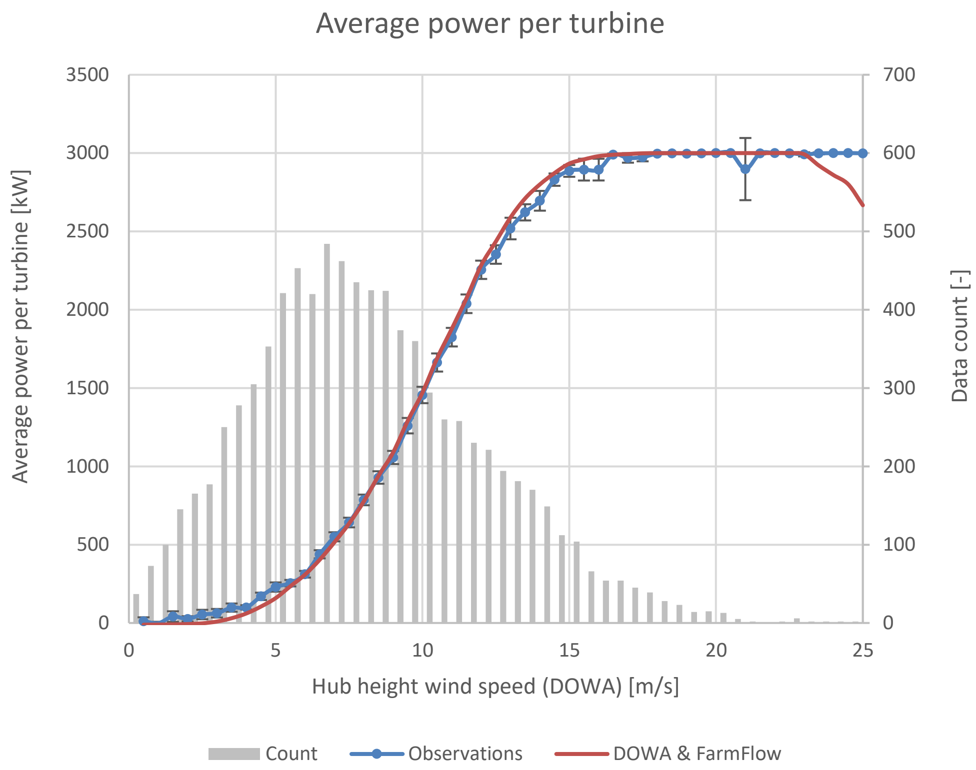

Figure 5-2 Comparison of the measured and simulated average power productions per turbine in OWEZ, including 95% confidence intervals (error bars) and a histogram of the used datapoints per wind speed bin

Figure 5-3 shows a comparison of the average power of all turbines from the observations, the FarmFlow simulations with DOWA wind and from simulations with KNW wind. The differences between individual wind turbines are caused by three phenomena: climatologic differences, wake losses, and down time. For example, turbine 3 shows a reduced average power due to down time during a period of relatively high wind speed. The highest yield is produced by turbine 12 because of a combination of the lowest wake losses and the largest distance to the coast. The lowest average power is produced by turbine 14, mainly due to down time during periods of relatively high wind speed. Turbine 14 also has the lowest availability of 79%. The lowest average power production among turbines with high availability is accomplished by turbine 23, as a result of high wake losses in combination with a relatively small distance to the coast.

The simulated yield from FarmFlow with DOWA wind are very close to the observed yields. Although the simulations with KNW wind show almost the same trend between individual turbines, the yields are approximately 3% below the observed values. This difference between DOWA and KNW wind as input in the simulations is according to expectations, since the KNW time series show a 2% lower average wind speed in comparison with DOWA, which is in agreement with results from the validation study on DOWA [3].

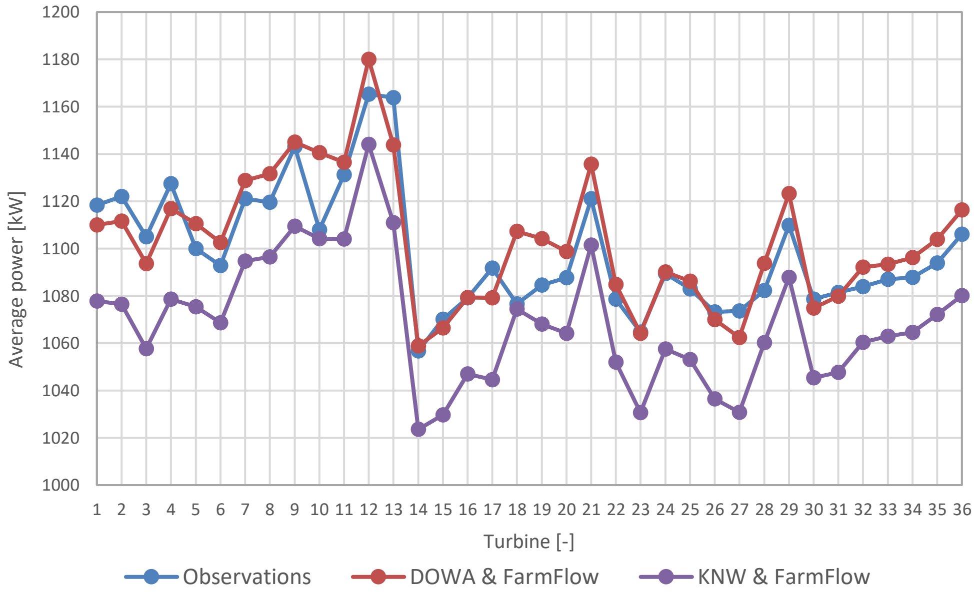

Figure 5-3 Comparison of the measured and simulated average power productions of individual turbines in OWEZ in 2010

In order to check consistency, Figure 5-4 shows the bias of the average turbine yields from the simulations with DOWA wind from 2010. The yields of two turbines, number 10 and 18, are almost 3% below the simulated yield, while for all other turbines the difference between measured and simulated yield is smaller than ±1.8% with an average of -0.24%. Especially turbine number 10 produces much less than its neighbours. Unfortunately, addressing possible causes of underperformance of individual wind turbines fall outside the scope of this study. Nevertheless, it is fair to say that turbines 10 and 18 most likely had a technical problem (such as yaw misalignment) causing the underperformance. Therefore, the results of these two turbines will be excluded in the following correlation analysis.

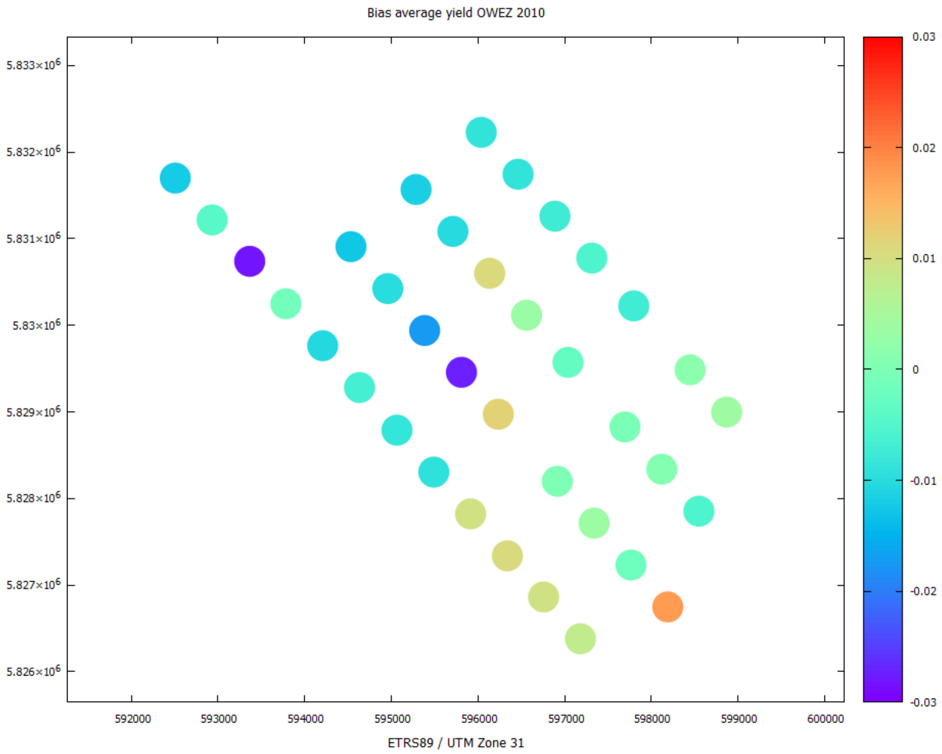

Figure 5-4 Bias of the simulated average yield of the OWEZ turbines in 2010 with DOWA wind

Figure 5-5 shows the correlation plot of measured and simulated average production per turbine. The slope of the linear least-squares regression line has a slope of 0.999 and an R^2 value of 0.88. The standard error is 0.15%.

The same procedure has been repeated with KNW wind as input in the FarmFlow simulations. The slope of the linear least-squares regression line with KNW wind is 0.966. The values for R^2 and the standard error with KNW wind are equal to the values with DOWA. This means that after calibration of the slope with a measure-correlate-predict method, the accuracy of wind farm yield estimations with DOWA and KNW wind are identical. Without calibration however, DOWA performs better than KNW. The differences found between the results with DOWA and KNW are in line with the results of the validation study [3], where it was found that DOWA represents the vertical wind shear better than KNW.

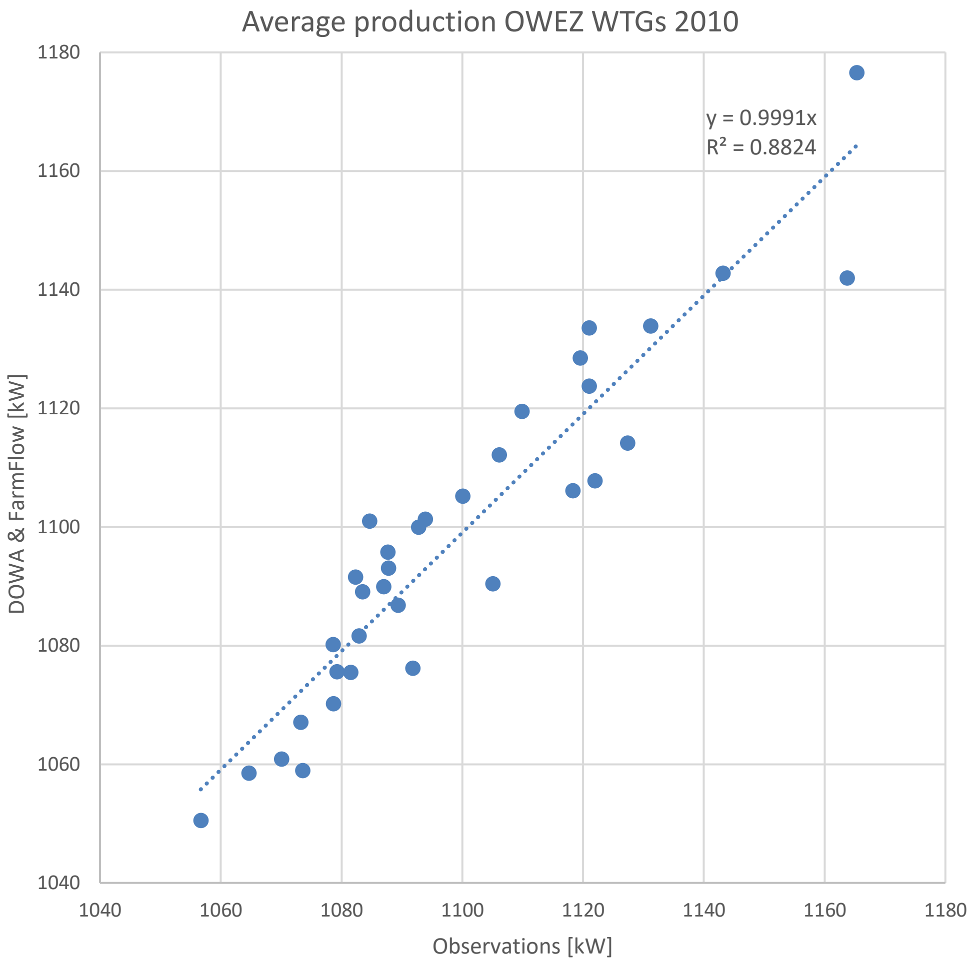

Figure 5-5 Correlation plot with linear least-squares regression of measured and simulated average productions of 34 OWEZ wind turbines in 2010

6 Conclusions

Wind turbine power measurements from the Offshore Wind farm Egmond aan Zee (OWEZ) in 2010 have been used to compare wind farm power curve predictions with DOWA and KNW as input in ECN's wind farm design tool FarmFlow. For both DOWA and KNW, the standard error of the yield predictions per turbine is 0.15%. The slope of the linear least-squares regression line with DOWA is 0.999 and with KNW 0.966, while the R^2 values are 0.88 for both DOWA and KNW.

When the time series of the wind atlas are calibrated with a measure-correlate-predict method (MCP), both wind atlases will perform similar. Without calibration, DOWA benefits from a more accurate prediction of the vertical wind shear, resulting in better predictions of offshore wind farm yields in the North Sea.

7 References

[1] E.T.G. Bot. FarmFlow validation against full scale wind farms, 2015.

[2] IEC 2018, IEC 61400-12-1 Wind energy generating systems – Part 12-1: Power performance measurements of electricity producing wind turbines, Edition 2.0 2017-03.

[3] J. B. Duncan, I. L. Wijnant, and S. Knoop. DOWA validation against offshore mast and LiDAR measurements, TNO report R10062, 2019.