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OWEZ WIND FARM EFFICIENCY

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Abstract

NoordzeeWind carries out an extensive measurement and evaluation program as part of the OWEZ project. The technical part of the measurement and evaluation program considers topics as climate statistics, wind and wave loading, detailed performance monitoring of the wind turbines, etc.
The measured wind resource is reported in half year reports, as well as the wind turbine performance. This report describes wake measurements and the efficiency of the wind farm, as measured during the period between 01-01-2007 and 31-03-2008.

The project is carried out under assignment of NoordzeeWind BV.

Acknowledgement

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Project information

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Contents

Offshore wind farm Egmond aan Zee seen from Egmond aan Zee beach.
(© L. Janssen)

Offshore wind farm Egmond aan Zee during installation, including meteomast near wind turbines 7 and 8.
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Executive Summary

Within the framework of the extensive measurement and evaluation programme NSW-MEP the effect of wind turbine wakes on energy output has been evaluated in the OWEZ wind farm, based on the SCADA measured 10-minute electric power and availability of the individual machines. The evaluation resulted in a global overall wind farm efficiency.
The wind farm performance has been determined using sector-wise power curves of the whole wind farm. The wind turbine nacelle anemometer has been used to establish the upstream wind speed in the applied wind direction sectors. The nacelle wind speed measurement has been corrected to the undisturbed wind speed via the NTF (Nacelle Transfer Function) determined with turbine #8 and the nearby meteo mast. The annual energy production AEP has been calculated using a representative offshore wind regime per applied sector.

The wind farm efficiency is the ratio of the annual energy production based on the sector-wise power curves and the AEP of the turbines applied at the same location but not affected by surrounding machines. As a reference the power curve of turbine #8, measured with the meteo mast wind speed, has been used. The analyses resulted in a wind farm efficiency of 93.4%. This result is based on a period of 15 months of SCADA data. Only data has been used when wind turbine were 100% available.
In case the average energy production is based on the average power of the 12 turbines in row one, determined with undisturbed wind coming from south-west, the derived efficiency is 91.5%.
For verification purposes the wind farm efficiency has been calculated with the ECN-code FLUXFARM using the same configuration and wind regime. The calculated efficiency is 91.7%; giving confidence to the derived analyses results.

Furthermore the wake effects between wind turbines in a row and between rows has been visualised. It is shown that wind turbines in a row (mutual distance is 7.2 rotor diameters) have a maximum drop in output power of almost 40%. Wakes of wind turbines between rows (11.1*D) have a maximum drop in power of about 27%. The power decrease appeared to be not depending on the number of upstream turbines.

1. Introduction

NoordzeeWind carries out an extensive measurement and evaluation program (NSW-MEP) as part of the OWEZ project. NoordzeeWind contracted Bouwcombinatie Egmond (BCE) to build and operate an offshore wind farm plus a meteorological mast. After the data have been validated, BCE delivers the measured 10-minute statistics data to NoordzeeWind. ECN created a database under assignment of NoordzeeWind and fills the database with the delivered data. NoordzeeWind contracted ECN to report on the collected data.

The technical part of the measurement and evaluation program considers topics as climate statistics, wind and wave loading, detailed performance and status monitoring of the wind turbines, etc. Before installation of the wind farm, a 116m high meteorological mast has been installed to measure the wind conditions. This mast is in operation since the summer of 2005. After realisation of the wind farm, the mast will is also used to, among others, measure wind conditions in the wake of turbines, farm efficiency, perform mechanical load and power performance measurements.
This report contains the wind farm efficiency established on the basis of SCADA data gathered on all 36 wind turbines and wind data measured at the meteo mast in the wind farm. The considered measurement period is from 01-01-2007 until 31-03-2008.

In chapter 2 the measured data relevant for the wind farm efficiency analyses is described.

The approach on wind farm efficiency determination is described in chapters 3. The results are summarized in chapter 4.

Beside the wind farm efficiency, based on SCADA data, calculations with FLUXFARM have been carried out to verify the evaluation result. Chapter 5 gives the relevant information.

Finally multiple wake effects of wind turbines in a row, and between rows, have been visualised in chapter 6.

2. Measured data

2.1 Measured signals

For the present wind farm efficiency evaluation data have been used from the meteo mast and the SCADA systems of all 36 wind turbines. The measured signals in the SCADA systems are summarised in Table 1. The meteo mast instrumentation is described in an earlier report [2].

Table 1. *Measured signals*

Signal name in OWEZ database	**signal description**
TABLE turbstat.tsb_10min	
t_0 timestamp with time zone NOT NULL,	-- timestamp (start of the 10 minutes interval)
wtg integer NOT NULL,	-- Number of the turbine (1-36)
cnt_ambient_ok integer,	-- HourCounters Average AmbientOk Avg. counter in [s]
cnt_generator_1 integer,	-- HourCounters Average Gen1 Avg. counter in [s]
cnt_generator_2 integer,	-- HourCounters Average Gen2 Avg. counter in [s]
cnt_grid_ok integer,	-- HourCounters Average GridOk Avg. counter in [s]
cnt_grid_on integer,	-- HourCounters Average GridOn Avg. counter in [s]
cnt_run integer,	-- HourCounters Average Run Avg. counter in [s]
cnt_service integer,	-- HourCounters Average ServiceOn Avg. counter in [s]
cnt_total integer,	-- HourCounters Average Total Avg. counter in [s]
cnt_turbine_ok integer,	-- HourCounters Average TurbineOk Avg. counter in [s]
cnt_wind_ok integer,	-- HourCounters Average WindOk Avg. counter in [s]
cnt_yaw integer,	-- HourCounters Average Yaw Avg. counter in [s]
cnt_alarmactive integer,	-- HourCounters Average AlarmActive Avg. counter in [s]
first_alarm_no integer,	-- System Logs First Active Alarm No
alarm_par_1 integer,	-- First Alarm parameter 1 in 10 min frame
alarm_par_2 integer,	-- First Alarm parameter 2 in 10 min frame
TABLE turbstat.tsb_cum	
t_0 timestamp with time zone NOT NULL,	-- timestamp (start of the 10 minutes interval)
wtg integer NOT NULL,	-- Number of the turbine (1-36)
hr_ambient_ok double precision,	-- Cum. ambient_ok counter in [Hr]
hr_generator_1 double precision,	-- Cum. generator_1 counter in [Hr]
hr_generator_2 double precision,	-- Cum. generator_2 counter in [Hr]
hr_grid_ok double precision,	-- Cum. grid_ok counter in [Hr]
hr_grid_on double precision,	-- Cum. grid_on counter in [Hr]
hr_run double precision,	-- Cum. run counter in [Hr]
hr_service double precision,	-- Cum. service counter in [Hr]
hr_total double precision,	-- Cum. total counter in [Hr]
hr_turbine_ok double precision,	-- Cum. turbine_ok counter in [Hr]
hr_wind_ok double precision,	-- Cum. wind_ok counter in [Hr]
hr_yaw double precision,	-- Cum. yaw counter in [Hr]
TABLE turbstat.turbdata	
t_0 timestamp with time zone NOT NULL,	-- timestamp (start of the 10 minutes interval)
wtg integer NOT NULL,	-- Number of the turbine (1-36)
generator_rpm_stat real[],	-- Statistics of Generator RPM; 1=min,2=max,3=avg,4=stddev
rotor_rpm_stat real[],	-- Statistics of Rotor RPM; 1=min,2=max,3=avg,4=stddev
blades_pitch_stat real[],	-- Statistics of Blades Pitch Angle; 1=min,2=max,3=avg,4=stddev;
grid_prod_power_stat real[],	-- Statistics of Grid Production Power;1=min,2=max,3=avg,4=stddev
amb_windspeed_stat real[],	-- Statistics of Ambient WindSpeed; 1=min,2=max,3=avg,4=stddev
hv_trafo_phase_temp1_avg real,	-- HVTrafo Phase1 Temp. Avg.;
hv_trafo_phase_temp2_avg real,	-- HVTrafo Phase2 Temp. Avg.;
hv_trafo_phase_temp3_avg real,	-- HVTrafo Phase3 Temp. Avg.;
direction_avg real, -- Avg. direction;	-- Avg. Direction;
amb_temp_avg real,	-- Ambient Temp. Avg. Only available for turb 7 and 8 ;
wtg_available_tsb integer,	-- turbine availability signal in [%]

The measured signals from the SCADA systems are divided in 3 groups:

- turbstat.tsb_10min = status data over a 10 minute period
- turbstat.tsb_cum = cumulative status data started at latest reset
- turbstat.turbdata = statistics of analogue signals over the 10 minute period.

2.1.1 Meteorological mast

The meteorological mast is a lattice tower with booms at three heights: 21m 70m and 116m above mean sea level (MSL). At each height, three booms are installed in the directions north-east (NE), south (S) and north-west (NW) [1]. Sensors attached to the meteorological mast are described in [2]. The location of the meteorological mast is given in Table 2.

Table 2. *Coordinates of the meteorological mast at OWEZ*

	UTM31 ED50	WGS 84
x	594195	4º23'22,7" EL
y	5829600	52º36'22,9" NB

2.1.2 Data SCADA system

Data present in the database and used for the wind farm efficiency analyses are measured in the period from 1 January 2007 until 31 March 2008.
Key signals in the present analyses are:

- the produced wind turbine electric power (average value = *grid_pod_power_stat),*
- the nacelle anemometer wind speed signal (average value = *amb_windspeed_stat*), and
- the availability signal (*wtg_available_tsb*).

All information has been stored as 10 minute values.
The availability of these data, gathered during the considered period, is in Appendix C.

Wind turbine power
The electric power of each wind turbine is measured by the Scada system of that wind turbine. The data is stored as the average power during 10 minutes.
The signal name is: average value = *grid_pod_power_stat.*

Nacelle anemometer
All 36 wind turbines are equipped with an FT Wind Sensor. The FT702LT is a solid-state meteorological sensor, which uses patented Acoustic Resonance airflow sensing technique to measure accurately both wind speed and direction. (Vestas internal note on: Ambient sensors). These 36 sensors are calibrated by the supplier.
The signal name is: *amb_windspeed_stat.*

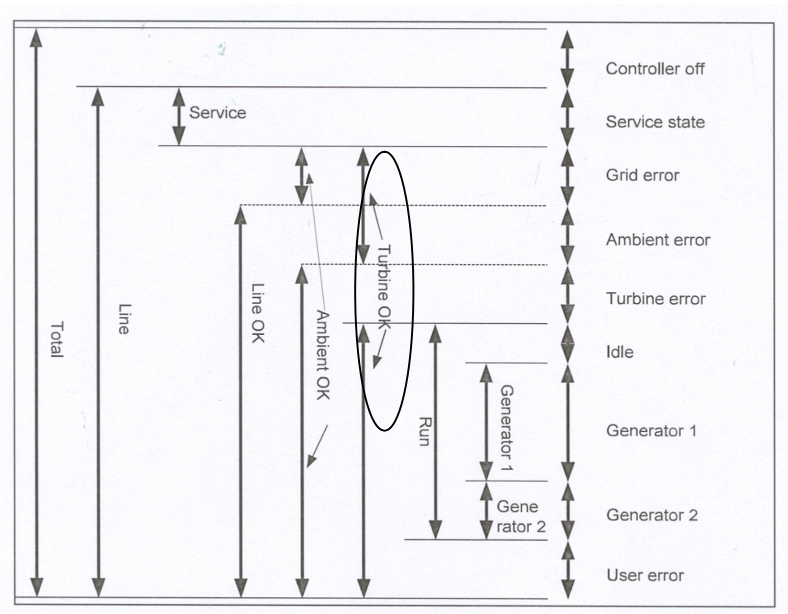

Figure 1. Differentiation of counter signals as gathered with the SCADA system. In the present evaluation 'Turbine_OK' has been chosen being representative for the wind turbine availability. (Vestas internal note 950173: Users Guide; chapter 5: production counters).

Definition of Availability

To evaluate the wake effects within the wind farm the availability of the wind turbines is an important parameter.

The availability signal, as defined and used in this analysis, is a composition of two SCADA measured counter signals:

1. *tsb_10min.cnt_turbine_ok:* giving the number of seconds, during 10 minutes, that the wind turbine status is OK (see figure 1) ;
2. *tsb_10min.first_alarm_no*: indicating if some fault occurred during the 10 minutes and/or not yet being reset.

The turbine availability signal *'wtg_available_tsb'* is the [%] of time, during the 10 minutes, that the machine is OK under the condition that the signal: *first_alarm_no* = 0 (no fault).

For further evaluation in the present report only data have been used with the wind turbine availability = 100%.

2.2 Sensor calibration

The applied sensors in the meteorological mast are calibrated according to maintenance schedules of BCE (Mierij Meteo). The cup anemometers are calibrated at DEWI Germany. BCE (Mierij Meteo) calibrates the other sensors. The calibration constants are applied to the data during the stage of data processing at BCE (Mierij Meteo) [2].

The nacelle anemometers and electric power sensors as deployed on all 36 wind turbines are not calibrated within this scheme. This means that the measurement uncertainties of these sensors are not determined according to common practice within the power performance determination, and in fact are unknown. The available measurement results have been assessed by means of plausibility checks of individual power curves using the nacelle anemometers; see paragraph 3.4 and appendix A.

2.3 Data validation

The quality and consistency of the SCADA data is assessed by means of manual check of the received data on:

1. Consistency
2. Out of range numbers
3. Followed by marking of incorrect and unavailable records

Corrupt or missing data fields are marked by error values (-999999).

The meteo data has been checked within the framework of the meteo data reporting.

Signal availability relevant for this report is given in Appendix C.

2.4 Data transport

The data checked by OWEZ are sent to ECN, where the data are collected in the OWEZ database.

2.5 Database content

The signals that are measured at the meteorological mast at OWEZ are indicated in [2].

The statistics data for each of the signals are the:

10-minute average value
10-minute minimum value
10-minute maximum value
10-minute standard deviation

An overview of the availability of data for each meteo mast signal is included in [2].

2.6 Layout of the wind farm

The wind farm efficiency depends on the layout of the farm. Important parameters are the shape (i.e. cluster, line, etc.) of the wind farm, the distances between wind turbines and rows of turbines, and the orientation with respect to the dominating wind direction.
The OWEZ wind farm layout and orientation is as shown in figure 2 [1]. In this figure the meteo mast location has been indicated as well.
The rows of turbines are oriented in the south-east to north-west direction (135 - 315 dgr.), perpendicular to the dominating wind direction: south-west.

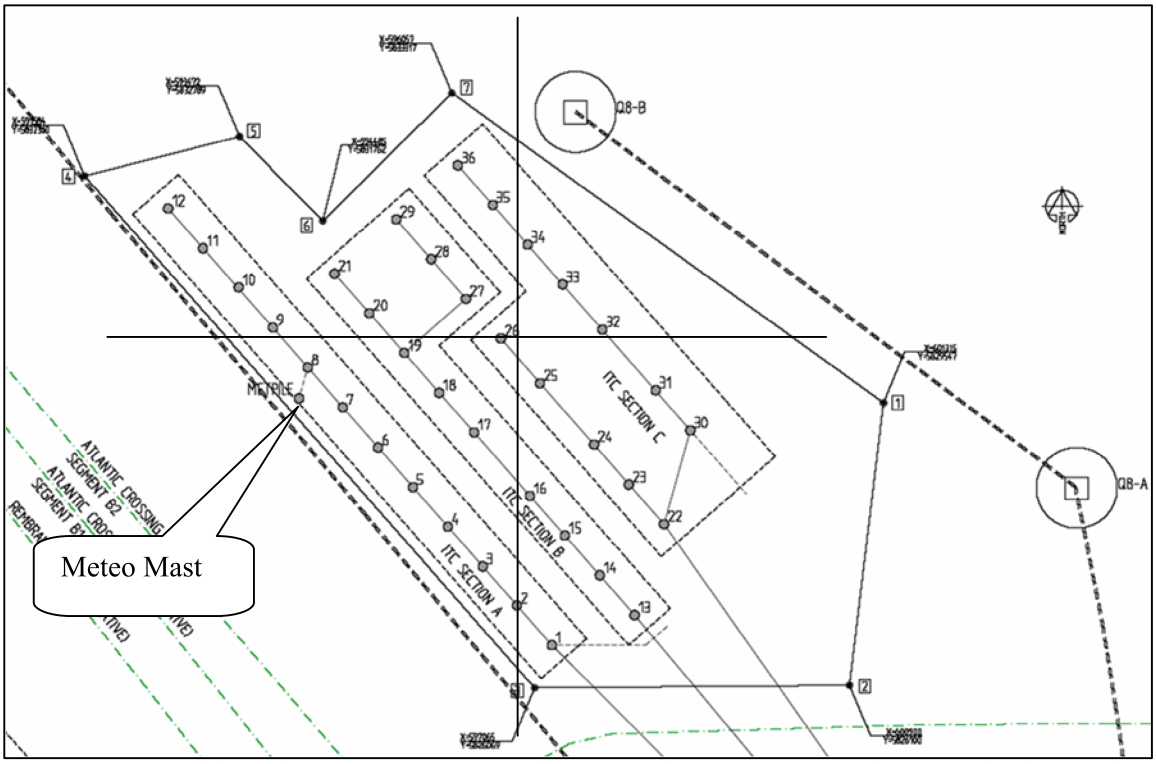

Figure 2. Wind farm lay-out. Four rows of wind turbines are oriented perpendicular to the dominating south west wind direction. The meteo mast is positioned close to turbines #7 and #8 [1]

3. Determination of Wind Farm Efficiency

3.1 Definition

In the wake of a wind turbine the wind speed is reduced and turbulence is increased relative to the undisturbed wind speed. Wind turbines placed in a cluster or array operate in the wakes of their neighbours, depending on their position in the farm and the wind direction. These influences will have effect on the energy yield of the whole wind farm. The magnitude of the energy deficit depends on the number of turbines and the design of the array itself, the spacing between the wind turbines and the orientation with respect to the dominating wind direction.
The wind farm efficiency is defined here as the ratio of the total energy output of the wind farm and the energy output of the 36 solitary wind turbines at the same location when not affected by surrounding wind turbines (reference output).

The wind farm energy output is based on the measured power of the individual wind turbines.
In this report the reference energy output is primarily based on the measured power performance of turbine #8 [6] and derived annual energy production AEP. This result is derived according to the standard IEC 61400-12.
Secondly the reference has been based on the calculated energy output of the mean power performance of the turbine 1 - 12 (row 1) with wind coming from south-west; this second reference is used for reasons of comparison, in order to get confidence in the resulting efficiencies having a different origin.

3.2 Approach

Originally the establishment of the wind farm efficiency was planned to be based on measured energy output of the individual wind turbines. After reviewing the actual data it appeared that the overall availability of the wind turbines in the considered period was 80%, ranging between 60 and 95% for the different individual wind turbines. A wind farm efficiency based on these energy output data would become too uncertain. For that reason it was decided to determine the wind farm efficiency on sector-wise power curves derived from the present power data and wind turbine availability.

The following procedure has been applied in this case:

1. Take four 90 degrees wind direction sectors, based on wind farm orientation.
2. Determine the four sector-wise power curves from the whole wind farm, using the nacelle anemometers of the upfront wind turbines in that sector.
3. Calculate the potential annual energy production applying the power curves and a representative sector-wise distribution of the wind regime.
4. Determine the wind farm efficiency in relation to the reference energy production (in this report both references are used for reasons of comparison).

3.3 Use of Nacelle Anemometer

Every wind turbine is equipped with a solid state nacelle anemometer, type FT702LT. This sensor can be used as a wind speed measurement device at the location of the wind turbines within the wind farm.
A fair indication of the local average wind speed within the array is possible when using the NTF: Nacelle Transfer Function [4]. This is the relation between the measured nacelle wind speed and the undisturbed wind speed, seen by the wind turbine.

The NTF, between the meteo mast and wind turbine #8, has been derived (according to the IEC committee draft [4] where possible) as a linear fit to the measured data, over the considered period. Here the meteo mast gives the undisturbed wind speed using the wind directions in the south-west sector.
This NTF, between meteo mast and wind turbine #8 (figure 3), has been applied to all nacelle anemometer measured wind speeds in the wind farm.

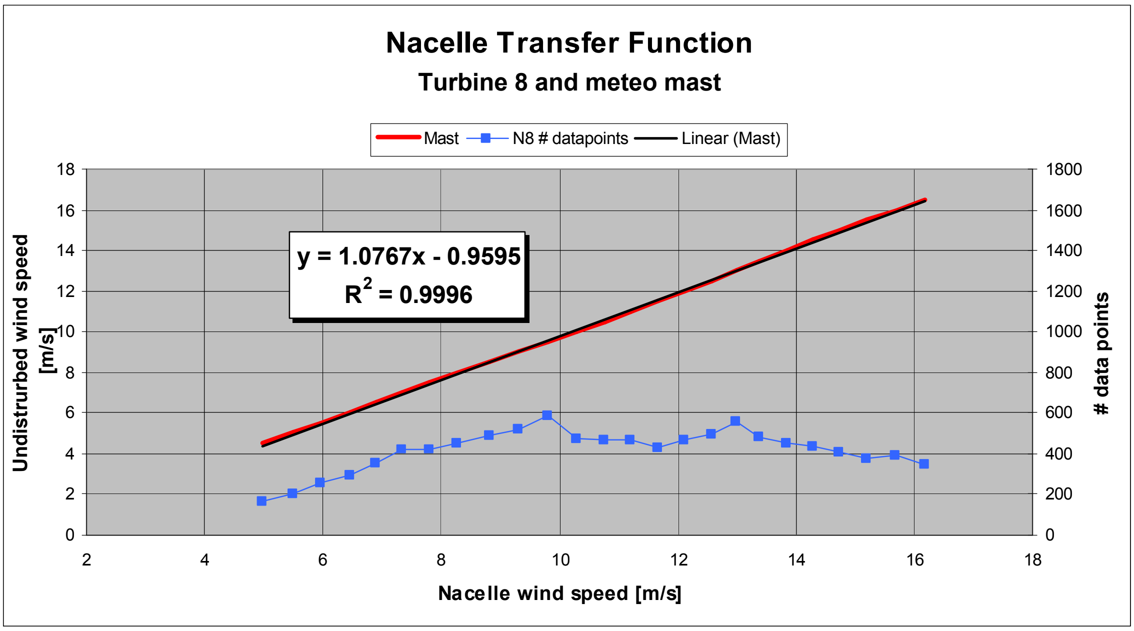

Figure 3. The NTF between the nacelle wind speed of turbine #8 and the undisturbed wind speed. The blue line is an indication of the amount of data points present.

3.4 Power performance of individual wind turbines

Power curves have been derived for all 36 wind turbines in the OWEZ wind farm. The reason to determine these power curves is to check whether the measured SCADA data of electric power and nacelle wind speed are plausible.
The wind speed for these power curves is the nacelle wind speed, of the individual machines, corrected to the undisturbed wind speed using the NTF as shown figure 3. An air density correction to $\rho = 1.225\ kg/m^3$ (sea level) has been applied. The power signal from the SCADA system has been used, representing the real mean electric power of the individual machines. Only power data has been used in case the wind turbine was available; independent from wind direction.
The resulting power curves are shown in Appendix A. These curves appeared to be plausible and globally correct, as expected. No serious deviations are present; the standard deviations of the power look normal. These data give confidence when used for the determination of the wind farm efficiency.
It must be mentioned that applying the nacelle anemometer transfer function NTF within the wind farm, when operating in the wake of other machines, is advised against in the draft of the standard [4]. The nacelle wind speed data of the machines inside the array and resulting performance curves are only used here for mutual comparison and assessment of the available data to be used for the wind farm efficiency determination, and not for absolute means.

The best results regarding the wind farm efficiency would be obtained if all wind turbines in the wind farm were in full operation during the considered period with 100% availability. However the availability is below 100% which affects the power performance of the individual machines

in the wind farm. The operational status of a wind turbine will influence the output of the neighbouring machines. This point gives an unknown uncertainty in the results. Filtering out the data during which all 36 machines are in operation, and using those data only, would lead to an unacceptable low amount of data to be used for further analyses.
It must be stressed that the derived power curves are not curves formally determined according to the present valid standard IEC 61400-12-1:2005. Deviations with respect to the standard are most regarding instrumentation, calibration requirements and wakes. The applied method to determine the wind farm efficiency is not a standardised method. Within the IEC a working group is drafting a standard for the determination of power curves of whole wind farms. The method applied in this report is part of the discussions.

4. Power curves and the wind farm efficiency

4.1 Sector-wise power curves

Four different power curves of the wind farm have been derived from the database. Each power curve is based on wind coming from different wind direction sectors. Based on the orientation of the wind farm the following four global power curve sectors have been chosen (see also figure 2):

- sector 1: 0 - 90 degrees;
- sector 2: 90 - 180 degrees;
- sector 3: 180 - 270 degrees;
- sector 4: 270 - 360 degrees.

The wind speed used for these 4 sector-wise power curves is the NTF corrected nacelle wind speed on top of the wind turbines in the first rows upstream to the wind direction. The turbine nacelle wind speed is used in case the wind turbine is in operation: i.e. is available. When not available the neighbouring wind turbine with undisturbed incoming wind flow was used.
In this case nacelle anemometers of those wind turbines are used positioned at the edges looking upwind. These turbines are not in a wake of their neighbours and application of the NTF (figure 3) is allowed [4].

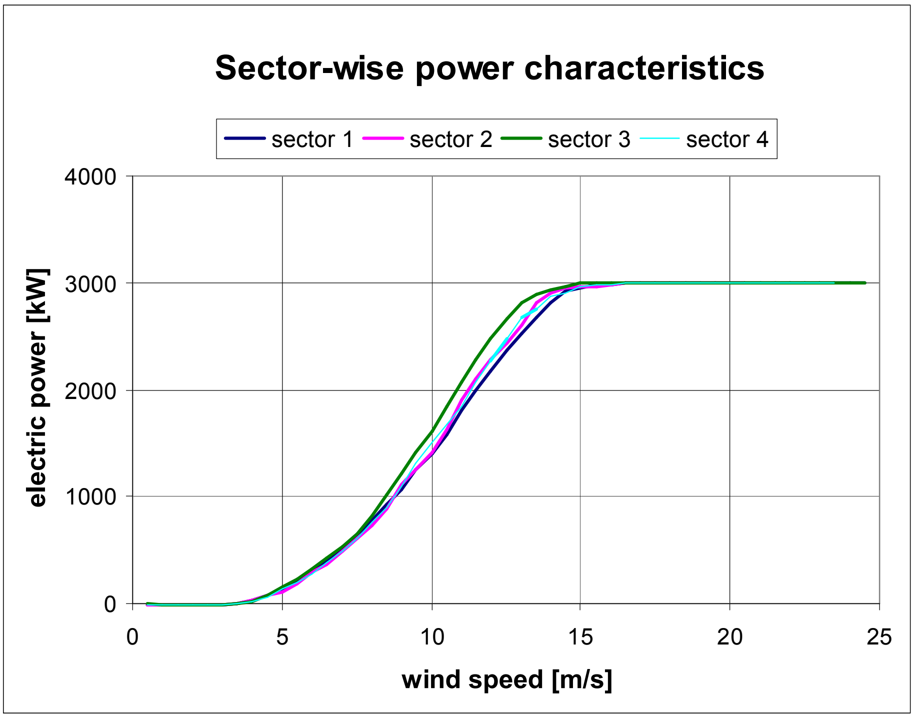

Figure 4. Resulting power curves of the whole wind farm in four wind direction sectors

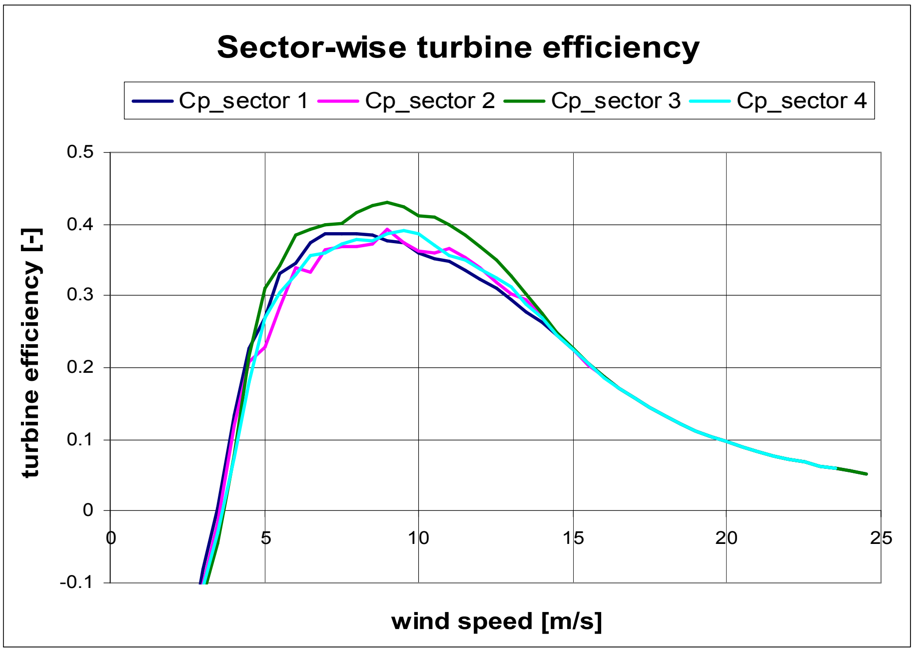

Figure 5. Wind turbine efficiency of the four sector-wise power curves.

The four resulting sector-wise power curves, as shown in the figures 4, are presented as the mean power of all 36 wind turbines. The four power curves are slightly different. The differences between the four sectors are most clearly shown with the derived wind turbine efficiencies in figure 5. The wind turbine efficiency in sector 3, south west, is most dominating as may be expected.

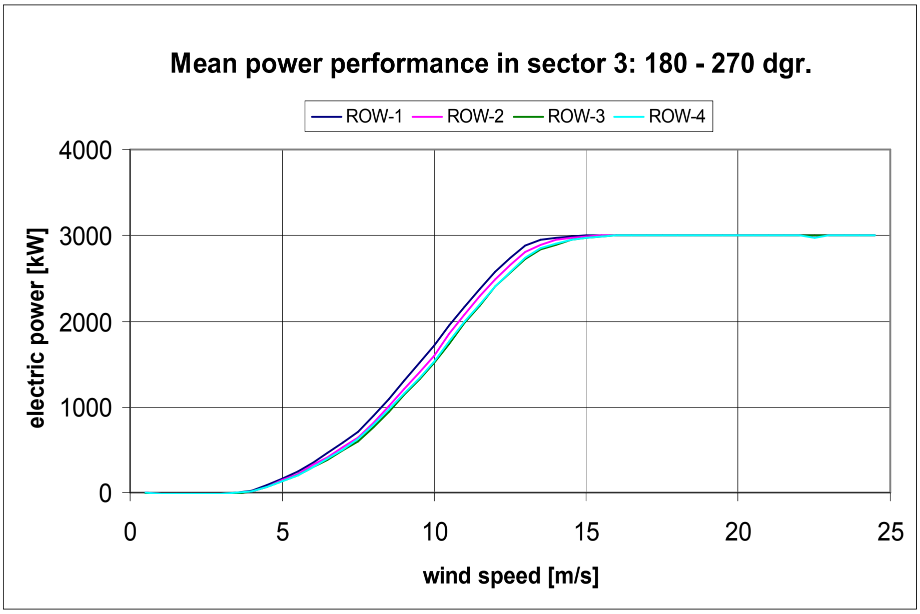

Figure 6. The power curve of sector 3, distinguished in power curves of the four successive rows of turbines, relative to the south-west wind direction. Row 1, with undisturbed wind, gives the best output.

The different rows of wind turbines, with the wind in sector 3, can be distinguished, as shown in figure 6. Row 1 contains 12 of the 36 machines. So in sector 3 one third of the wind farm is in an undisturbed wind condition resulting in a higher average power level.

4.2 Resulting wind farm efficiency

To establish the wind farm efficiency the power curves in the 4 sectors (figure 4) must be compared with the power performance of the solitaire wind turbine not affected by surrounding wind turbines. This comparison is carried out on the basis of calculated annual energy production AEP. For this purpose a sector wise wind regime has been taken from The Dutch Offshore wind atlas [5] and transferred from 12 sectors to the 4 sectors as applied in this analysis. Two location representative annual average wind speeds have been used here, as reported in the Power performance measurement report of turbine #8; i.e.: I = 9.2 m/s and II = 8.42 m/s. [see table 11 of ref. 6].

The wind speed distributions as applied in the energy production calculation are summarised in table 3. Per sector (1 - 4) the average wind speed and frequency of occurrence (fraction of the time) are given. For instance sector 3 (180-270 dgr.) has the highest wind speed and the wind within this sector occurs most (36.8%) of the time; as to be expected.
The applied wind regimes are assumed to be Weibull distributed in all sectors; distribution is either: k = 2.31 at U = 9.2 m/s or k = 2 at U = 8.42 m/s [6].

Table 3: Assumed wind regime per selected wind direction sector.

Wind regime = 9.2 m/s and k = 2.31

sector	annual average wind speed U [m/s]	frequency distribution f(U) [-]
1	8.18	0.167
2	8.44	0.265
3	10.24	0.368
4	9.16	0.201

Wind regime = 8.42 m/s and k = 2

sector	annual average wind speed U [m/s]	frequency distribution f(U) [-]
1	7.48	0.167
2	7.72	0.265
3	9.37	0.368
4	8.38	0.201

Furthermore the reference wind energy output must be determined.
Within this analysis two reference wind energy outputs have been chosen:
Ref. 1. The AEP (extrapolated) as given in the power performance document [6].
Ref. 2. For reasons of comparison the AEP based on the average power performance of 12 wind turbines in row one, determined with wind in sector 3.

Based on these two energy output references the wind farm efficiencies are calculated and summarized in table 4. This results for wind regime I: 9.2 m/s, k = 2.31, is given in figure 7 with two blue dots (diamants).

Table 4: Resulting OWEZ wind farm efficiencies.

Representative local wind regime	Ref. 1.	Ref. 2.
I: 9.2 m/s; k = 2.31	93.4 %	91.6 %
II: 8.42 m/s; k = 2.0	93.3 %	91.4 %

To establish wind speed dependency the wind farm efficiency has been calculated as a function of annual average wind speeds additionally. The results are shown in figure 7. The yellow line results using Ref.1 (official power curve) as reference energy output. The calculated efficiencies appear to be rather independent of the wind regime.
The purple line represents the results using the mean power of the first row (Ref.2) as reference energy output and a slight dependency with wind regime is shown.

Both lines are calculated with Rayleigh distributed wind regimes (k = 2).

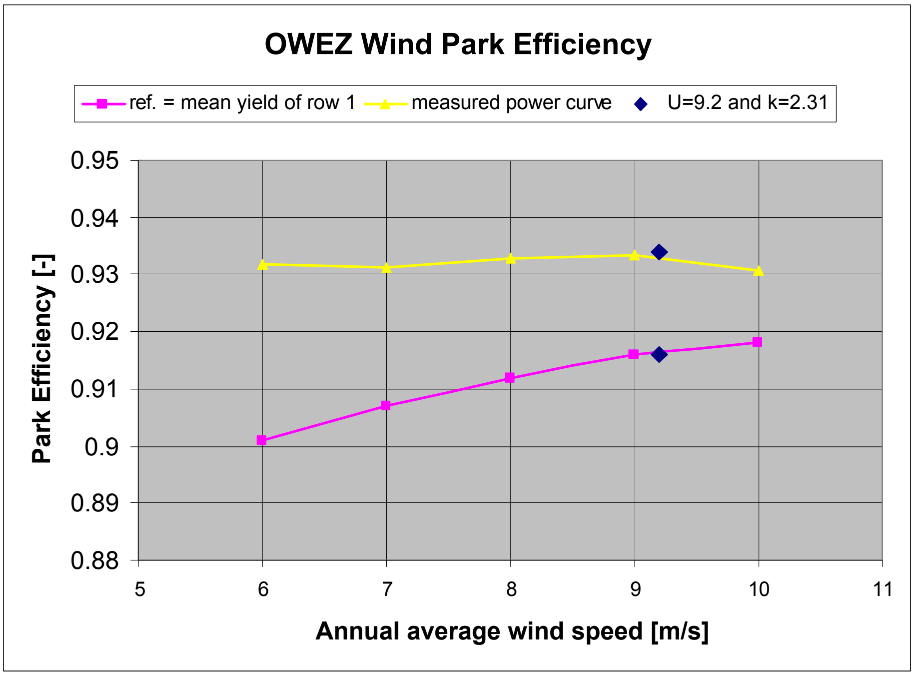

Figure 7. Resulting wind farm efficiencies as a function of annual average wind speed based on two different reference energy productions. The two blue dots are the results shown in table 4 (wind regime I: 9.2 m/s; k = 2.31).

4.3 Summary and Limitations of the result

In conclusion it can be stated that the wind farm efficiency of the OWEZ wind farm is between 91.4 and 93.4 % for the local annual average wind speed of about 9 m/s. For offshore conditions the resulting efficiency is nearly independent from the local wind regime. This result is derived from measured SCADA data of all 36 wind turbines and data measured at the meteo mast near wind turbine #7 and #8, measured period 01.01.07 and 31.03.08. The result has been determined on derived sector-wise power curves with data of the Scada measured average power, availability and nacelle wind speed. The reason for this approach was the fact that the availability of the wind turbines in the considered period was well below 100%, meaning that the wake conditions altered during the considered period. The amount of data, during 15 months however is considered to be well enough that the result may be seen as representative.

The results however contain uncertainties because of the following issues.
1. Wind turbine availability
The wind turbines in the wind farm did not have 100% availability during the considered period; but 80% in average. This means that the electric power of the individual machines was measured when neighbouring turbines could be out of operation and varying wake effects were present.
2. Nacelle wind speed sensor
The nacelle anemometer has been used to determine the sector-wise power curves of the wind farm. The NTF (nacelle transfer function) has been determined between the sensor on turbine #8 and the meteo mast representing the undisturbed wind speed. This NTF has been applied to the other wind turbines. However this #8 anemometer and other nacelle anemometers are not calibrated officially, differences between anemometers could be present.

3. Applied wind regime distribution

In this analysis a wind speed distribution per wind direction sector has been assumed. The real wind that blew through the wind farm during the considered period is different. But there are no serious differences expected in the wind sector distribution of the applied wind regime and the real wind regime. This will not have an effect on the derived wind farm efficiencies.

5. Calculated wind farm efficiency

The wind farm configuration has been evaluated with the ECN code FLUXFARM [9].
Input for the calculations were:

- the wind farm configuration as shown in figure 2.
- the measured power curves of the V90 wind turbine [6]
- the wind speed distribution per sector as summarized in table 3.

The resulting calculated total wind farm efficiency is 91.7 %, see table 5. This is close to the result as described in paragraph 4.2.

Table 5: *Resulting OWEZ wind farm efficiencies plus FLUXFARM calculations.*

Representative local wind regime	Ref. 1.	Ref. 2.	FLUXFARM
I: 9.2 m/s; k = 2.31	93.4 %	91.6 %	91.7 %
II: 8.42 m/s; k = 2.0	93.3 %	91.4 %	91.8 %

Within the Upwind project the FLUXFARM code recently participate in a Benchmark with other wind farm calculation codes like WAsP. The FLUXFARM results appeared to be close to the reference wind farm: Hornsrev measurements. On the basis of the Benchmark exercise [10] FLUXFARM has been upgrade to FLOWFARM.
This means that the results as shown in chapter 4 of the report are convincing.

6. Wake effect

Wind farm efficiency is the result of wake effects from one wind turbine to another in the wind farm. In a wake the wind speed is lower and the turbulence is higher relative to the undisturbed wind speed. The OWEZ wind farm is built in 4 rows of machines perpendicular to the expected dominant south-west wind direction. The rows are separated 1.000 m (11.1 * D) from each other and the wind turbines in a row are separated about 645 m (7.2 * D). There is a bigger gap between turbines 16 - 17, 24 - 25 and 31 - 33, due to soil conditions. This can clearly be observed in figure 2.
In several directions multiple wake effects are present, both within the rows and between the rows. Analyses have been made to visualise the wake effects between turbines during situations that they are in each others wake. This resulted in the following figure 8.

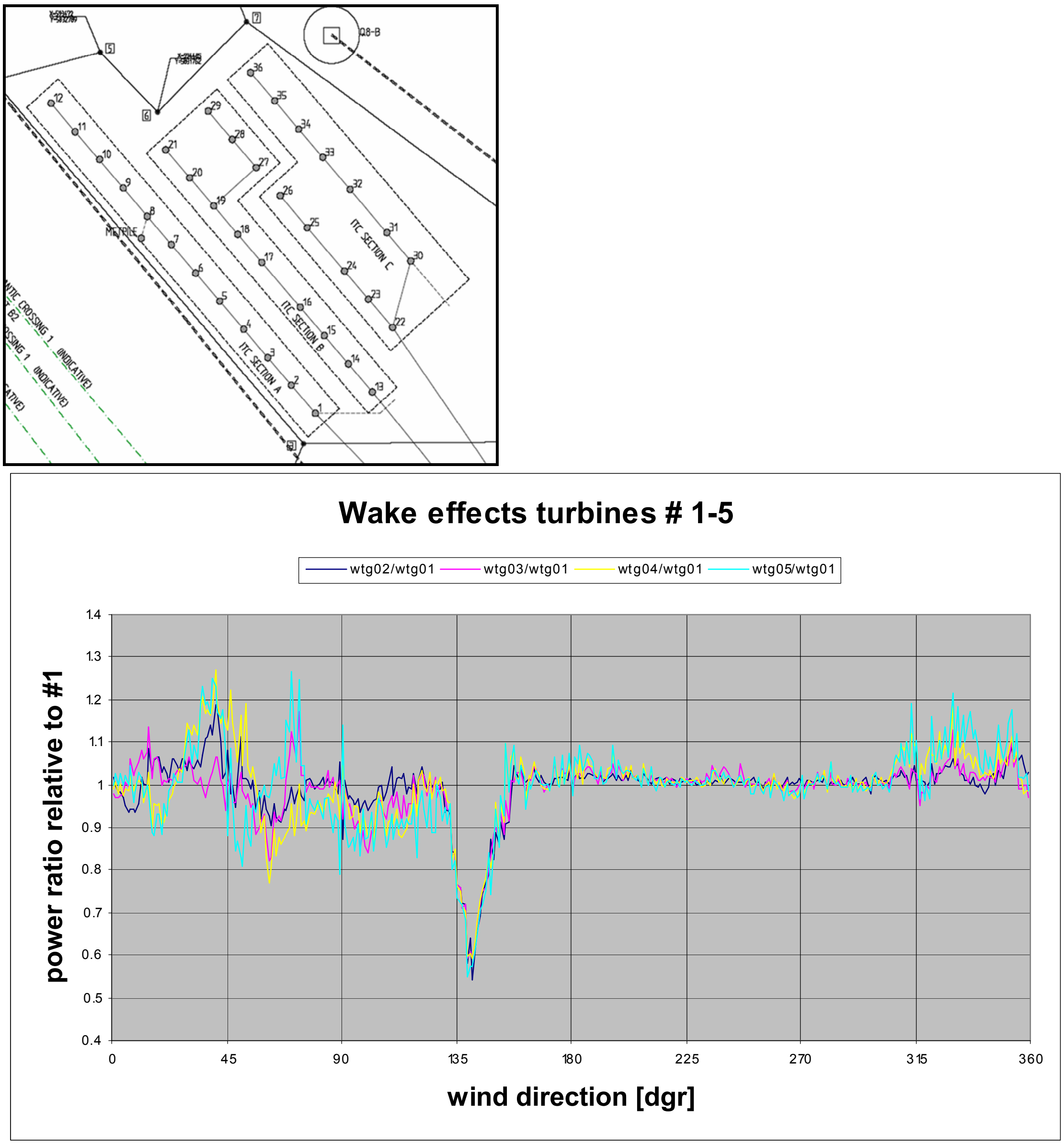

Figure 8. Multiple wake effects of the wind turbines # 1 - 5, relative to turbine #1 as a function of wind direction. The dominating effect is clearly present at 140 dgr. On top the farm layout is shown for orientation purposes.

In figure 8 the ratios of measured electric power between the wind turbines # 2, 3, 4 and 5 relative to turbine 1 are plotted as a function of wind direction. Only data have been used in case all 5 upstream wind turbines are available and the turbine power is between 10% and 90% of its nominal power. The wind direction has been taken from the meteo mast. One degree bins have been used.
It is clearly shown that the wind turbine power drops significantly when the wind is coming from about 140 dgr. direction; when the turbines are in a full wake situations. The drop in power of the 4 turbines in the wakes is to below 60% and there is almost no difference in power deficit between machines in single wake #2 or multiple wakes #3, 4 and 5. The same outcome has been found with the test wind farm at the ECN Wind Turbine Test Station Wieringermeer EWTW [7, 8].
The dip at about 140 dgr. in figure 9 has been enlarged in figure 10.

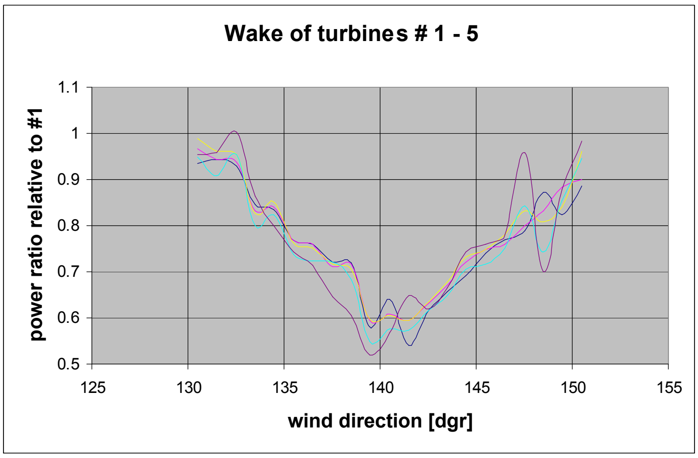

Figure 9. Detail of figure 8 showing the close wake effects.

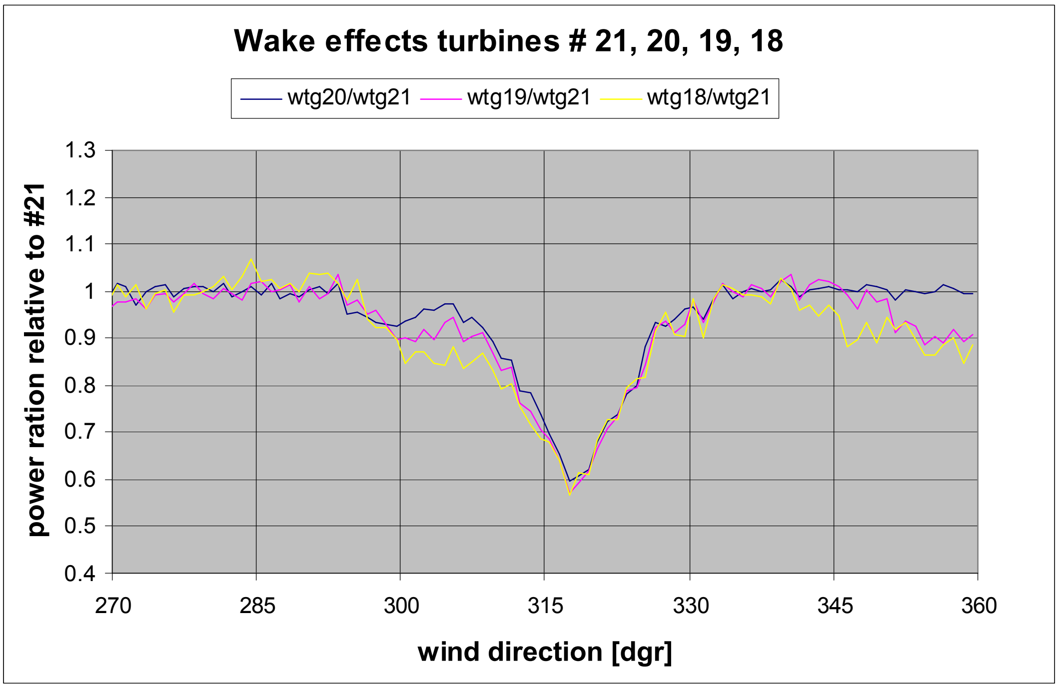

Figure 10. Multiple wake effects of the wind turbines # 18 - 20, relative to turbine #21 as a function of wind direction. The dominating effect is clearly present at 318 dgr.

Similar results are found in between rows of wind turbines with wind coming from other directions. Look for the turbine numbers in the farm layout on top of figure 8.

Figure 10 shows the wake effect with wind coming from the north-west direction. A similar dip as shown in figures 8 + 9 is present in the direction of 318 dgr. Moreover it is clearly shown that the turbines # 18 and 19 are affected when the wind is coming from north, and turbine #20 is not.

The next figure 11 shows the effects of the wind turbines #29, 21 and 9 (north-west part of the farm) relative to turbine #36. The turbines are in each others full wake at 50 dgr wind direction and the loss in power is about 25%. It is also clearly shown that turbine #9 is in the wake of turbines # 10, 11 and 12 at 320 dgr with a power drop of almost 40%. The two different multiple wake situations are summarised in table 6 for turbine #9.

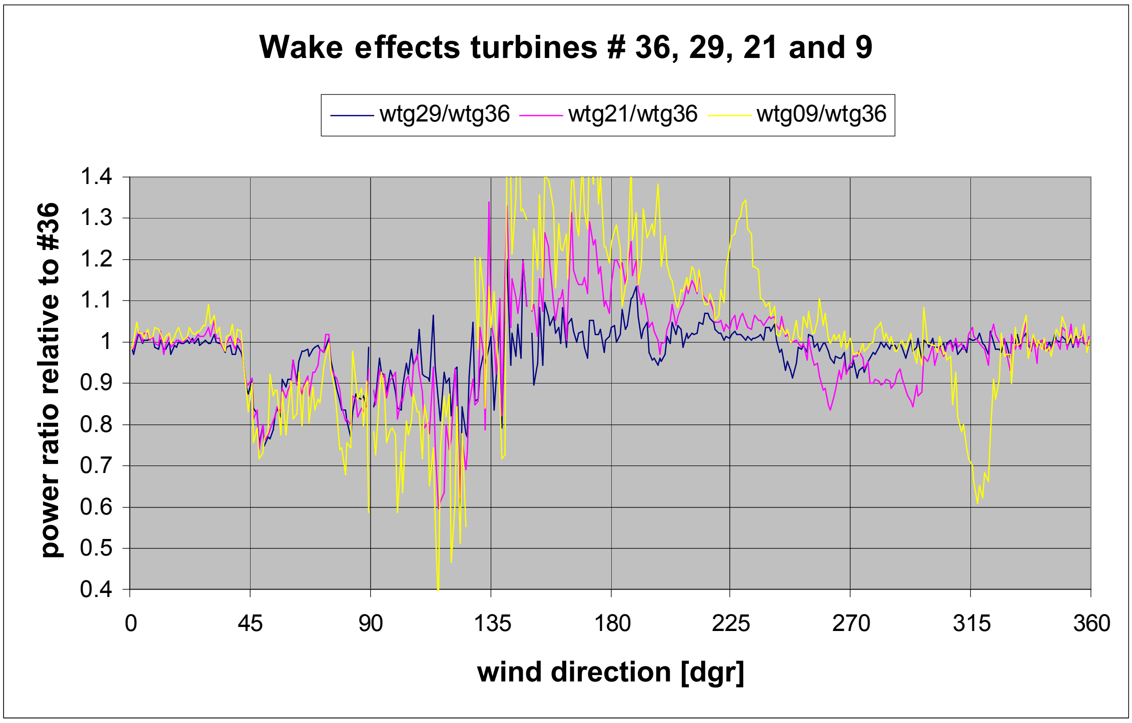

Figure 11. Multiple wake effects of the wind turbines # 9, 21, 29, relative to turbine #36, as a function of wind direction.

Table 6. Turbine #9 in multiple wakes from two directions.

Wind direction [dgr]	Distance between turbines [m]	Power ratio [%]
50	1000	73
320	645	61

7. Conclusions

Within the framework of the extensive measurement and evaluation programme NSW-MEP the effect of wind turbine wakes on energy output has been evaluated in the OWEZ wind farm, based on the SCADA measured 10-minute electric power and availability of the individual machines. The evaluation resulted in a global overall wind farm efficiency.
The wind farm performance has been determined using sector-wise power curves of the whole wind farm. The wind turbine nacelle anemometer has been used to establish the upstream wind speed in the applied wind direction sectors. The nacelle wind speed measurement has been corrected to the undisturbed wind speed via the NTF (Nacelle Transfer Function) determined with turbine #8 and the nearby meteo mast. The annual energy production AEP has been calculated using a representative offshore wind regime per applied sector.

The wind farm efficiency is the ratio of the annual energy production based on the sector-wise power curves and the AEP of the turbines applied at the same location but not affected by surrounding machines. As a reference the power curve of turbine #8, measured with the meteo mast wind speed, has been used. The analyses resulted in a wind farm efficiency of 93.4%. This result is based on a period of 15 months of SCADA data. Only data has been used when wind turbine were 100% available.
In case the average energy production is based on the average power of the 12 turbines in row one, determined with undisturbed wind coming from south-west, the derived efficiency is 91.5%.
For verification purposes the wind farm efficiency has been calculated with the ECN-code FLUXFARM using the same configuration and wind regime. The calculated efficiency is 91.7%; giving confidence to the derived analyses results.

Furthermore the wake effects between wind turbines in a row and between rows has been visualised. It is shown that wind turbines in a row (mutual distance is 7.2 rotor diameters) have a maximum drop in output power of almost 40%. Wakes of wind turbines between rows (11.1*D) have a maximum drop in power of about 27%. The power decrease appeared to be not depending on the number of upstream turbines.

The method applied in this analyses has some unknown uncertainties:

1. The limited availability of the turbines during the considered measurement period. The average wind farm power output sometimes is slightly too high because of non operating neighbouring wind turbines.
2. The application of the nacelle transfer function to non calibrated sensors of several machines in the farm.

Recommendation for future application
In this analyses 4 global sectors have been chosen based on the orientation of the farm relative to the assumed dominant wind direction. The effect of this choice has not been investigated here but it is recommended to know whether an effect is present. This could be done in the present IEC work group preparing a standard on wind farm power performance determination .

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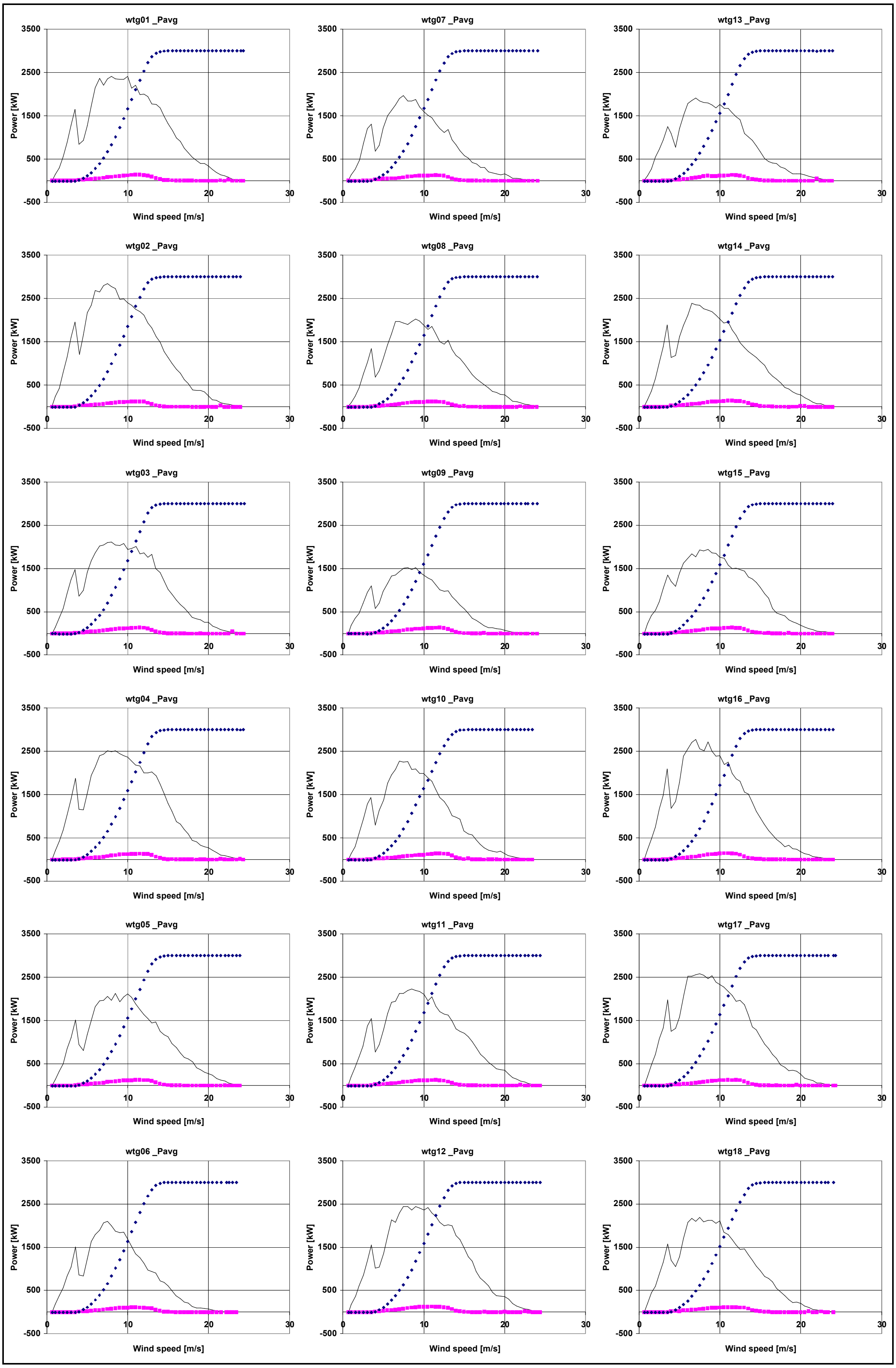
Appendix A Power performance curves of 36 turbines

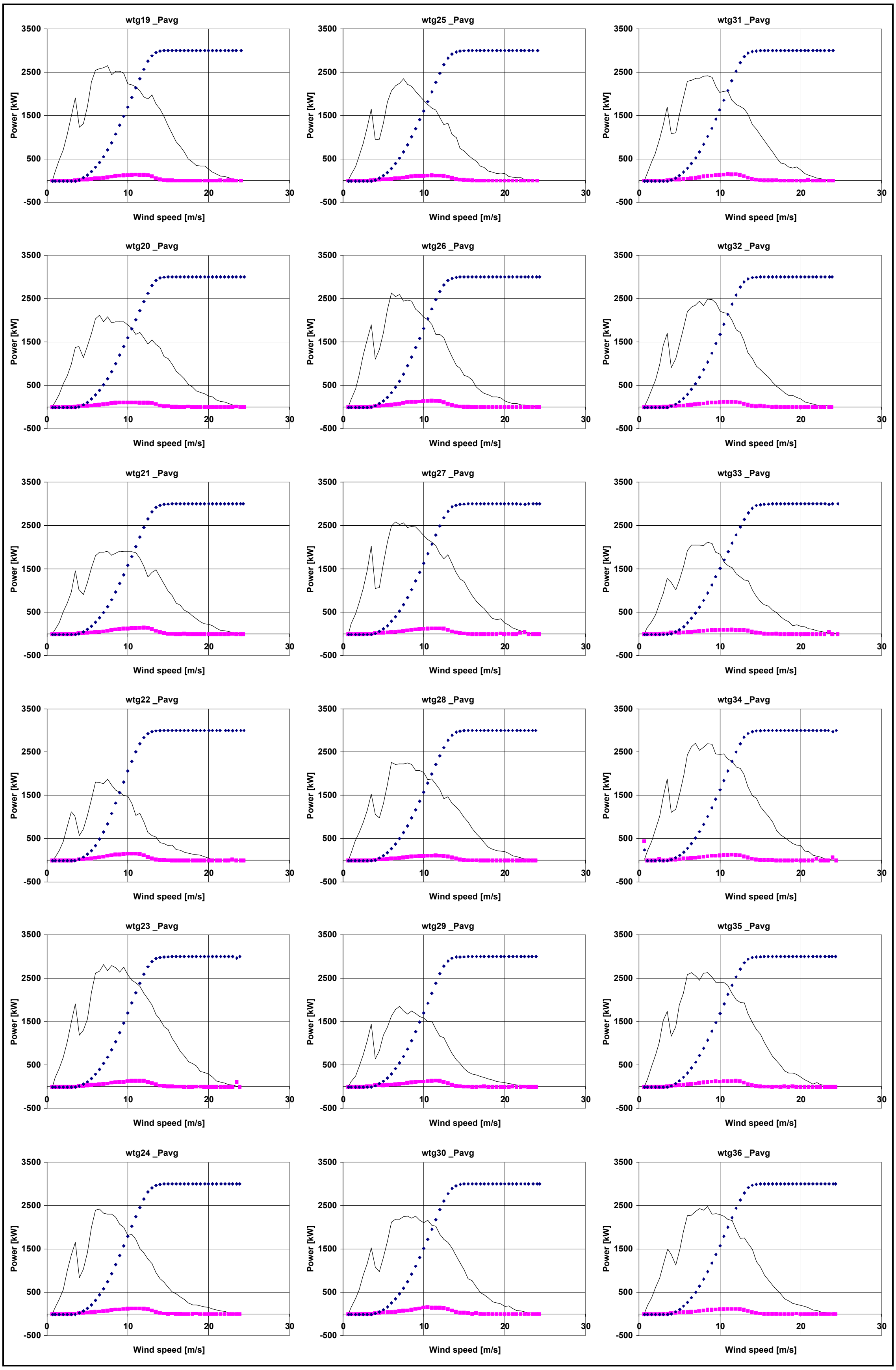
On the next two pages all 36 power performance curves are shown.
These curves have been put together on the bases of the measured electric power and the nacelle anemometer wind speed gathered with the Scada system. The nacelle anemometer wind speed is corrected to undisturbed wind speed via the NTF measured at wind turbine #8.

The 36 power curves are mutually slightly different. Reasons for these differences are:
Turbines operate in wake and non wake conditions; in fact the NTF is only for non wake conditions. Deviations due to this effect have not been investigated due to lack of information.
Turbines did not operate during 100% of the time of the considered period. So the wake situations in the wind farm are not always the same.

The 36 graphs show three lines:

1. the blue dotted line being the performance curve;
2. the red dots showing the standard deviation of the power within the wind speed bins;
3. the thin black line showing the number of data points available for the graph.


wtg01 _Pavg
wtg07 _Pavg
wtg13 _Pavg
wtg02 _Pavg
wtg08 _Pavg
wtg14 _Pavg
wtg03 _Pavg
wtg09 _Pavg
wtg15 _Pavg
wtg04 _Pavg
wtg10 _Pavg
wtg16 _Pavg
wtg05 _Pavg
wtg11 _Pavg
wtg17 _Pavg
wtg06 _Pavg
wtg12 _Pavg
wtg18 _Pavg
Power [kW]
Wind speed [m/s]
3500
2500
1500
500
-500
0
10
20
30


wtg19 _Pavg
wtg25 _Pavg
wtg31 _Pavg
wtg20 _Pavg
wtg26 _Pavg
wtg32 _Pavg
wtg21 _Pavg
wtg27 _Pavg
wtg33 _Pavg
wtg22 _Pavg
wtg28 _Pavg
wtg34 _Pavg
wtg23 _Pavg
wtg29 _Pavg
wtg35 _Pavg
wtg24 _Pavg
wtg30 _Pavg
wtg36 _Pavg
Power [kW]
Wind speed [m/s]

Appendix B Availability of the Status (counter) signals

The table in this appendix shows the availability of relevant signals used in the wind farm efficiency analyses: electric power, nacelle wind speed and turbine availability (see par 2.1.2).
A data availability of 100% means that all three signals were present during the whole month. In case the 10-minute value of one of the signals was not present that 10 minute statistic did not count for this overview and has not been used in the analyses.

An overall data availability of 90% is present over the considered period of 15 months.

	2007												2008			
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	overall
wtg01	100%	99%	100%	100%	93%	81%	100%	100%	99%	48%	100%	99%	100%	100%	100%	95%
wtg02	100%	99%	100%	100%	100%	100%	100%	100%	99%	100%	100%	98%	100%	100%	100%	100%
wtg03	100%	99%	100%	100%	100%	100%	100%	100%	99%	41%	100%	99%	100%	99%	100%	96%
wtg04	100%	99%	100%	100%	100%	100%	92%	95%	82%	92%	99%	69%	100%	100%	100%	95%
wtg05	100%	99%	100%	93%	100%	100%	100%	100%	99%	51%	100%	99%	100%	100%	66%	94%
wtg06	49%	96%	100%	100%	98%	100%	100%	100%	99%	99%	100%	99%	100%	61%	100%	93%
wtg07	100%	100%	100%	100%	99%	96%	100%	100%	99%	100%	100%	99%	100%	22%	2%	88%
wtg08	100%	96%	100%	100%	99%	100%	100%	100%	99%	33%	0%	53%	100%	100%	100%	85%
wtg09	100%	100%	100%	77%	100%	100%	99%	100%	99%	92%	97%	51%	0%	0%	0%	74%
wtg10	54%	100%	100%	100%	99%	100%	100%	100%	99%	100%	100%	99%	100%	63%	0%	88%
wtg11	100%	99%	100%	64%	100%	100%	100%	100%	99%	100%	100%	99%	73%	95%	100%	95%
wtg12	100%	99%	100%	94%	95%	92%	99%	99%	88%	100%	87%	94%	100%	86%	82%	94%
wtg13	60%	99%	100%	100%	100%	100%	100%	100%	99%	4%	0%	0%	0%	63%	100%	68%
wtg14	100%	97%	85%	100%	99%	100%	100%	100%	99%	100%	97%	99%	100%	100%	100%	98%
wtg15	100%	100%	100%	25%	96%	100%	100%	100%	99%	100%	100%	97%	100%	100%	100%	94%
wtg16	100%	100%	100%	100%	100%	100%	100%	99%	99%	100%	100%	99%	81%	100%	100%	98%
wtg17	100%	99%	100%	100%	97%	100%	100%	100%	90%	100%	97%	99%	100%	100%	100%	99%
wtg18	55%	99%	97%	100%	100%	100%	100%	100%	99%	91%	100%	99%	95%	100%	100%	96%
wtg19	83%	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%	99%	100%	100%	100%	99%
wtg20	82%	100%	100%	100%	100%	94%	100%	100%	99%	33%	0%	52%	100%	100%	100%	84%
wtg21	100%	100%	100%	100%	100%	100%	87%	100%	99%	43%	0%	47%	56%	100%	100%	82%
wtg22	100%	100%	100%	87%	91%	100%	100%	100%	70%	0%	0%	0%	0%	0%	0%	56%
wtg23	100%	99%	100%	87%	80%	100%	100%	100%	99%	100%	100%	98%	100%	100%	100%	98%
wtg24	100%	99%	100%	87%	91%	100%	96%	100%	99%	100%	58%	99%	100%	67%	0%	86%
wtg25	100%	100%	100%	87%	91%	100%	100%	100%	99%	100%	100%	36%	0%	37%	91%	83%
wtg26	39%	100%	100%	86%	91%	100%	100%	100%	99%	97%	100%	99%	54%	97%	100%	91%
wtg27	100%	98%	90%	100%	100%	100%	100%	100%	99%	100%	94%	99%	100%	100%	100%	99%
wtg28	82%	97%	89%	100%	100%	100%	100%	100%	99%	100%	100%	99%	100%	49%	0%	88%
wtg29	82%	100%	91%	100%	100%	100%	100%	100%	99%	43%	0%	0%	0%	74%	100%	73%
wtg30	100%	99%	100%	87%	91%	100%	100%	100%	89%	99%	100%	99%	100%	100%	46%	94%
wtg31	100%	99%	84%	84%	90%	100%	100%	100%	99%	100%	100%	99%	100%	97%	50%	93%
wtg32	100%	99%	100%	87%	91%	100%	100%	100%	99%	100%	100%	99%	75%	50%	100%	93%
wtg33	100%	99%	100%	87%	92%	100%	100%	100%	99%	100%	100%	36%	0%	53%	89%	84%
wtg34	100%	100%	100%	87%	91%	100%	100%	100%	99%	100%	100%	99%	100%	95%	100%	98%
wtg35	58%	100%	100%	87%	91%	100%	100%	100%	86%	100%	100%	99%	100%	100%	100%	95%
wtg36	100%	100%	100%	87%	91%	99%	100%	100%	99%	100%	82%	68%	100%	100%	100%	95%
overall																90%