Quick scan wind farm efficiencies of the Borssele location

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Abstract

ECN predicted the performance of four conceptual wind farms for the Borssele locations in assignment of the Ministry of Economic Affairs. The analyses have been performed with the FarmFlow and EE-Farm tools.

The four different wind farm designs were made by variation of the rotor power densities of 320 and 380 W/m^2, thus two different wind turbines models, and two different wind farm power densities of 6 and 9 MW/km^2, resulting in 4 designs.

Next to the energy yield and wind farm efficiencies the consequences of the different wind farms on the internal electrical grid designs will be predicted. The prediction will investigate the electrical efficiency and the cable cost determined by the cable length. Due to the fact that absolute cost are inaccurate to predict only the differences between the designs will be reported

In the assignment it is prescribed that the transport of the energy yield to the main grid onshore will makes use of the so-called plug socket @ sea (stopcontact op zee) option in the form of modular hubs of approximately 700 MW each to which the array cables are connected directly.

The capacity factor for the different design options varies between 45,5% and 50,5% depending on the parcel and wind farm and wind turbine power density. The wind farm efficiencies vary between 83,5% and 91,4% due to the different parcel and wind farm and wind turbine power density. The losses due to the Belgian Wind Farms, included in the overall wind farm efficiency, are calculated at approximately 4%.

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Appendices

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Introduction

In assignment of the Ministry of Economic Affairs of the Netherlands a quick scan study has been performed to investigate the potential of the Borssele location for the development of Wind Farms.

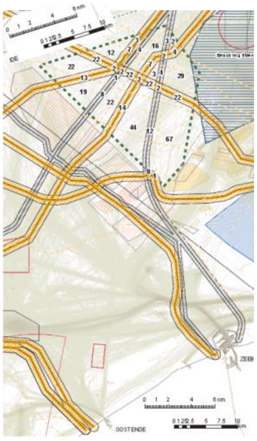

Figure 1 The location of the Borssele area

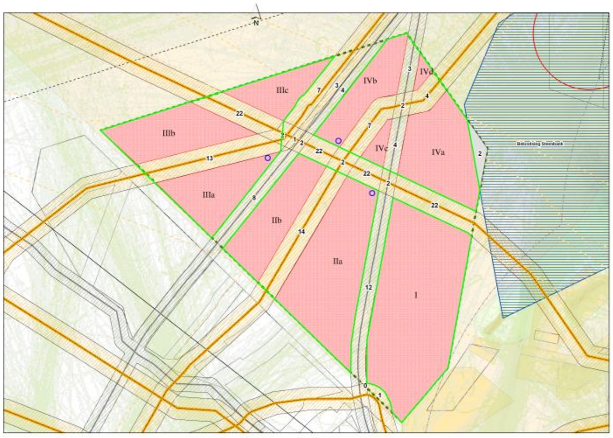

Figure 2 The proposed distribution in 4 parcels

In **Figure 1** is shown where the location Borssele for wind farm development is positioned. In **Figure 2** is shown what a possible choice is to divide the area into 4 parcels to be developed by developers.

The assignment consists of the analysis of 4 different wind farm lay-outs for the entire location. These 4 different wind farm lay-outs consist of 2 different wind turbine designs and two different wind farm power densities. After the wake analysis has been performed the results will be presented for four different parcels or lots being sub-area's that could be developed by different developers.
The wind turbine designs differ mainly with respect to the rotor power density and the rated power of the wind turbine. Each design will take account of the constraints that the cable /pipeline lanes will be clear of wind turbines. For power lines a safety zone of

500 m on both sides will be clear and for telecommunication lines a free area of 750 m on both sides will be clear. Due to the size of the converter stations at sea (stopcontact op zee) of approximately 700 MW the total size of the wind farms should be approximately in multiples of 700 MW. Thus wind farms with a nominal power of 700 or 1400 MW or possibly 2100 MW are analysed.

The gross area of the location Borssele is 344 km^2 but due to all the power and telecommunications lines the net area is much smaller approximately 230 km^2. For a 6 MW/km^2 PD this results in a total power around 1400 MW and for a 9 MW/km^2 PD the total power will be approximately 2100 MW.

An estimate of the wind conditions for the site has been made where a meso scale model has been used to estimate the effects of the (planned) wind farms on the Belgian side of the border, see Appendix A.

1.1 The wind turbines

The 2 wind turbine models used in the analysis have rotor power densities[1] of 320 W/m^2 and 380 W/m^2, and rotor diameters of 154 and 164 m, resulting in rated power of approximately 6 and 8 MW. The models used do not represent an actual wind turbine but will have state of the art performance characteristics. The used data to characterise the wind turbines are listed in the Appendix B.

1.2 The wind farm power density

The wind farm power density[2] (WF PD) will determine to a large extend the wind farm's array efficiency. The values chosen in the analysis are decided upon in mutual agreement with the ministry of Economic Affairs.
The used values for the WF PD are 6 and 9 MW/km^2.

1.3 The wind conditions at Borssele and the influence of the Belgian Wind Farms

The wind conditions at the Borssele location are determined using the database of wind conditions maintained by ECN. To take into account the effect of the wind farms on the Belgian side of the border an estimate has been made of the amount of energy that is taken out from the wind sectors that are influenced by the wind farms. Due to the fact that not all wind farms are known with respect to number of machines, type of the wind turbine and rated power it is not possible to make a detailed analysis.

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[1] The rotor power density is defined as that Rated (or nominal) power / Rotor area [W/m^2]

[2] The wind farm power density is defined as the wind farm rated power / gross area of the wind farm [MW/km^2]

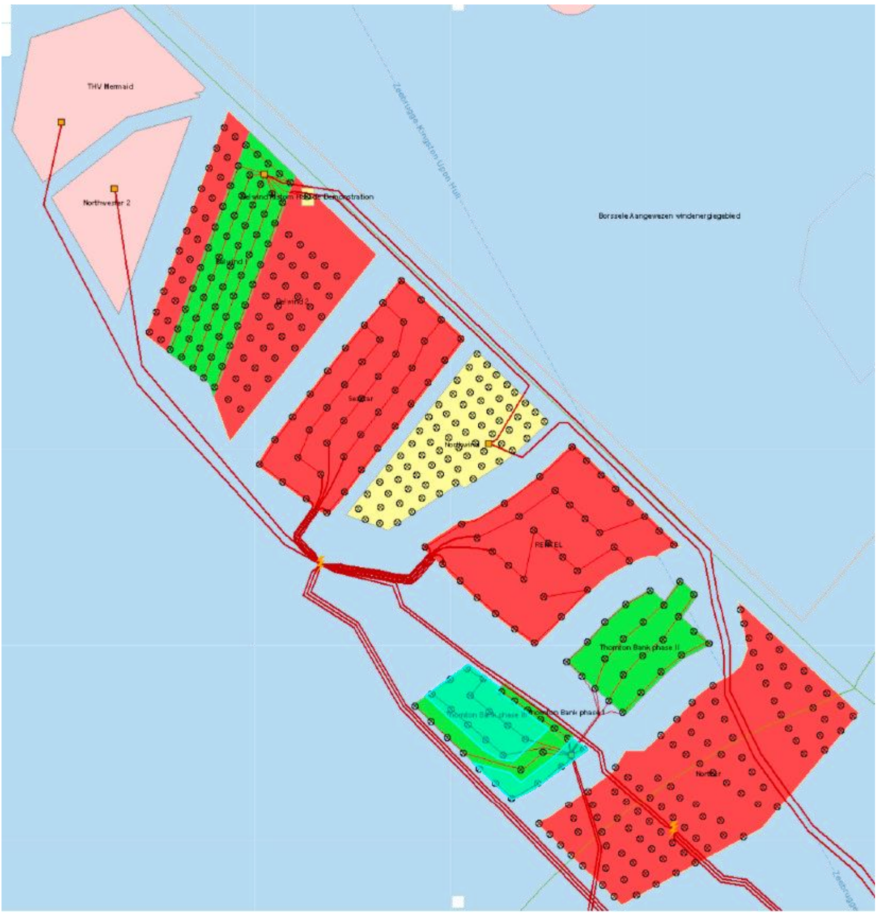

Figure 3: The (planned) Wind Farms on the Belgian side of the border.(http://www.4coffshore.com)

1.4 The wind farm design and analyses

The wind farm designs and analyses are performed with FARMFLOW. The FARMFLOW model is developed by ECN to predict the wind turbine wake effects of offshore wind farms, i.e. the reduction of the wind speed and the added turbulence behind the wind turbines. The model has been verified with measurements and compared to other models in numerous projects. See Appendix D for a more extensive description of the FARMFLOW model.

1.5 The electrical system

For the electrical system the four wind farm designs will be analysed with respect to the array cabling costs and the electrical losses. The analyses will be performed with the EE-FARM model developed by ECN, see for more detail of this model Appendix E.

The absolute values will not be presented due to the limited level of detail of this study: only the relative differences in comparison to each other are presented.

1.6 The results

The results will be presented for the total area and for the four different parcels. Each set of results will consist of the Energy Yield of the area, the capacity factor of the wind turbines and the array efficiencies for the four different conceptual designs.

2

The design and analysis of the 4 concepts

2.1 The wind conditions at the location Borssele

The wind conditions at the Borssele location are determined using the database of wind conditions maintained by ECN. A full period of 10 years (2003 – 2013) has been used to derive the wind data. The wind rose and turbulence rose are corrected to take into account the effect of the (planned) wind farms on the Belgian side of the border (see Figure 3). **Figure** 4shows the frequency rose of the wind directions. A rose of the average wind speed and turbulence intensity, including the effects of the Belgian wind farms, are shown in **Figure 5** and **Figure 6** respectively.

The effect of the wind farms on the Belgian side of the border is based on a wake analysis of an array of wind turbines comparing the ratio of the incoming wind and turbulence and the wind conditions behind the array of wind turbines.

Table 1: Wind climate Borssele location (Lat=51°42’03”, Lon=2°57’34”, H=105 m) assuming that the wind farms on the Belgian side of the border are all operational.

Sector	Frequency	Weibull A	Weibull k	Wind speed	Power density
	[%]	[m/s]		[m/s]	$[W/m^2]$
1 N	6.82	9.71	2.19	8.60	687.08
2 NNE	8.12	9.73	2.26	8.62	673.30
3 NEE	8.18	9.83	2.32	8.71	679.99
4 E	6.51	9.16	2.34	8.12	547.13
5 SEE	4.86	8.51	2.22	7.54	457.98
6 SSE	4.95	9.32	2.09	8.26	634.33
7 SWW	7.47	11.10	2.14	9.83	1046.30
8 SSW	13.34	12.05	2.41	10.68	1215.50
9 SWW	14.85	11.66	2.40	10.34	1104.80
10 W	10.50	10.97	2.19	9.72	989.53
11 NWW	7.82	10.75	2.07	9.52	981.06
12 NNW	6.57	10.41	2.06	9.22	895.40
All	**99.99**	**10.57**	**2.20**	**9.37**	**890.35**

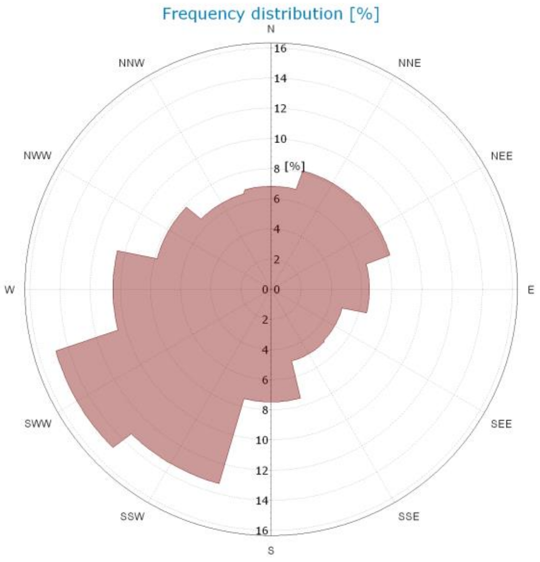

Figure 4: Frequency distribution of wind directions at the Borssele wind farm location.

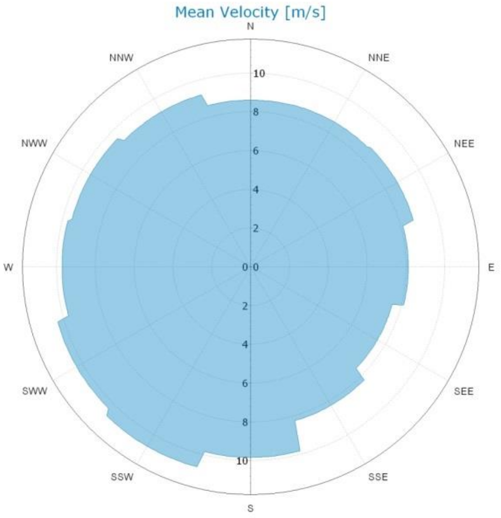

Figure 5: Mean wind speed rose at the Borssele wind farm location.

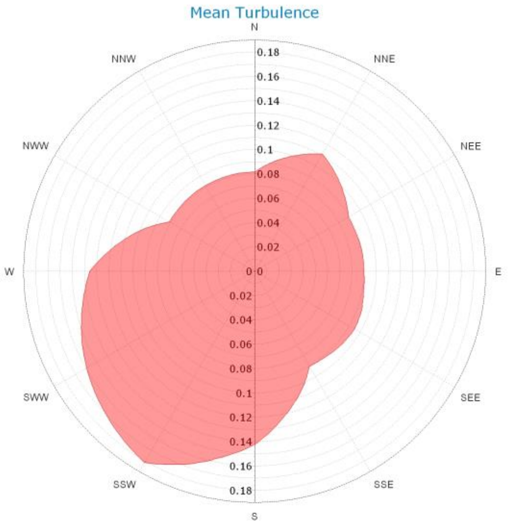

Figure 6: Turbulence rose derived for the Borssele wind farm location.

2.2 Description of the 4 designs

Four wind farm designs have been created, where each design is characterised by the Wind Farm Power Density (WF PD) and the Wind Turbine Power Density (WT PD). The wind farm power densities used in the designs is 6 and 9 MW/km^2 and the wind turbine or rotor power densities used are 320 and 380 W/m^2.

The wind turbine models are for a 6 MW, with a WT PD of 320 W/m2 and 8 MW with a WT PD of 380 W/m2. The wind turbines power and axial force curve are shown in Appendix B. The assumed hub height of the wind turbines is 30 m + half the rotor diameter.

Table 2: Criteria for the four wind farm designs.

Design	Rotor density [W/m^2]	Wind farm density [MW/km^2]	Prated [MW]	Rotor diameter [m]
1	320	9	6	154
2	380	9	8	164
3	320	6	6	154
4	380	6	8	164

The location Borssele has been divided into 10 area's on the basis of the intersection by the telecommunication cables. Four parcels as indicated in **Figure 7** by the green lines are chosen at forehand to get nearly equal spaces.

For each area the wind turbines are placed according to the speciation of the WF PD and the two different wind turbine models. The required free space around the telecommunication cables is respected.

Due to the large number of wind farms on the Belgian side of the border and the experience that decay of the wakes effects requires very large distances to really diminish it is decided to place wind turbines immediately at the border of the different parcels. This enables also the maximum distance between the wind turbines to comply with the agreed WF PDs.

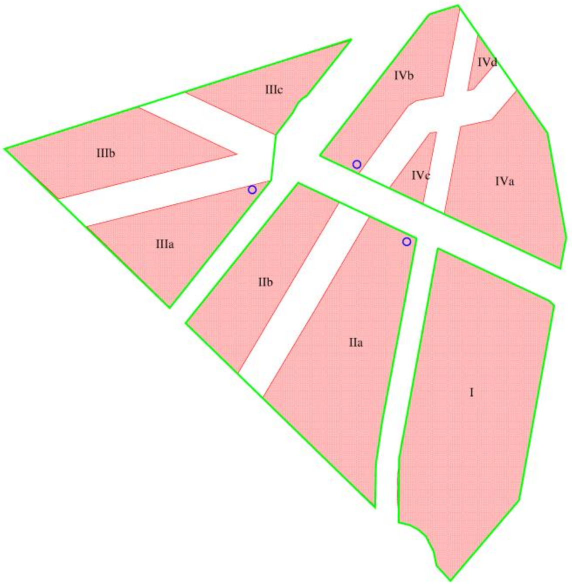

Figure 7: The 4 parcels for the location Borssele

The four designs are shown in the **Figure 8** - **Figure 11**. Each design consists of a different number of wind turbines based on the WF PD and the rated power of the wind turbine models.

Table 3: The nominal power of the Borssele location wind farm and number of wind turbines

Design	Number of wind turbines [-]	Nominal power [MW]
1	390	2340
2	300	2400
3	266	1596
4	200	1600

The number of wind turbines and rated power per lot are shown in the **Table 4**: Rated power and number of wind turbines per lot for each wind farm design.

Table 4: Rated power and number of wind turbines per lot for each wind farm design

Design	Parcel 1		Parcel 2		Parcel 3		Parcel 4	
	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]
1	95	570	100	600	110	660	85	510
2	74	592	76	608	86	688	64	512
3	66	396	68	408	75	450	57	342
4	49	392	52	416	57	456	44	352

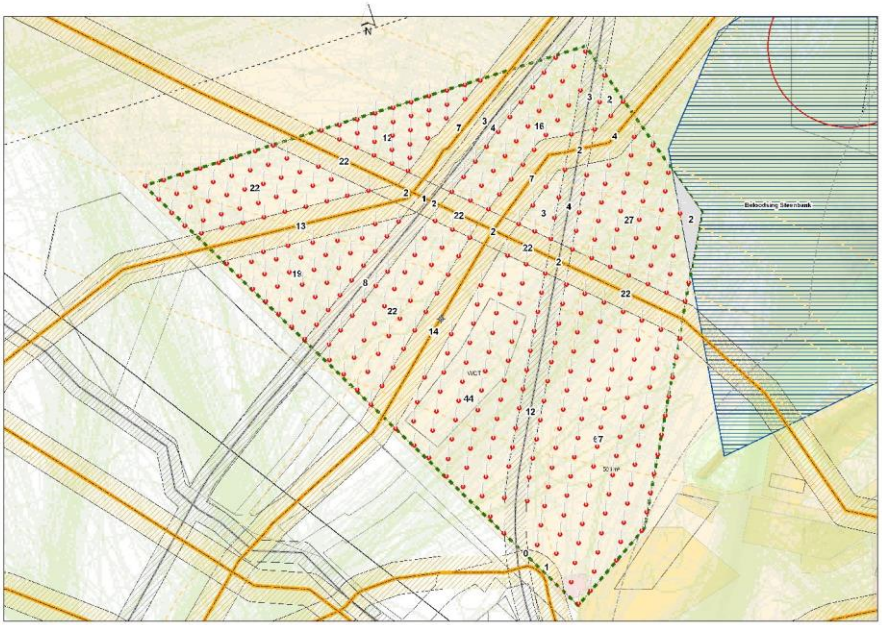

Figure 8: Layout of wind farm design 1.

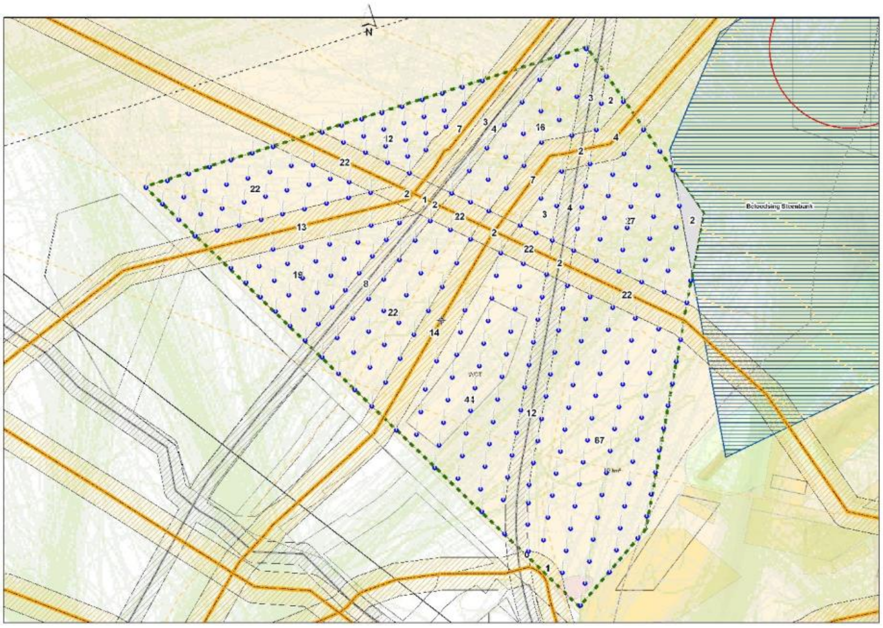

Figure 9: Layout of wind farm design 2.

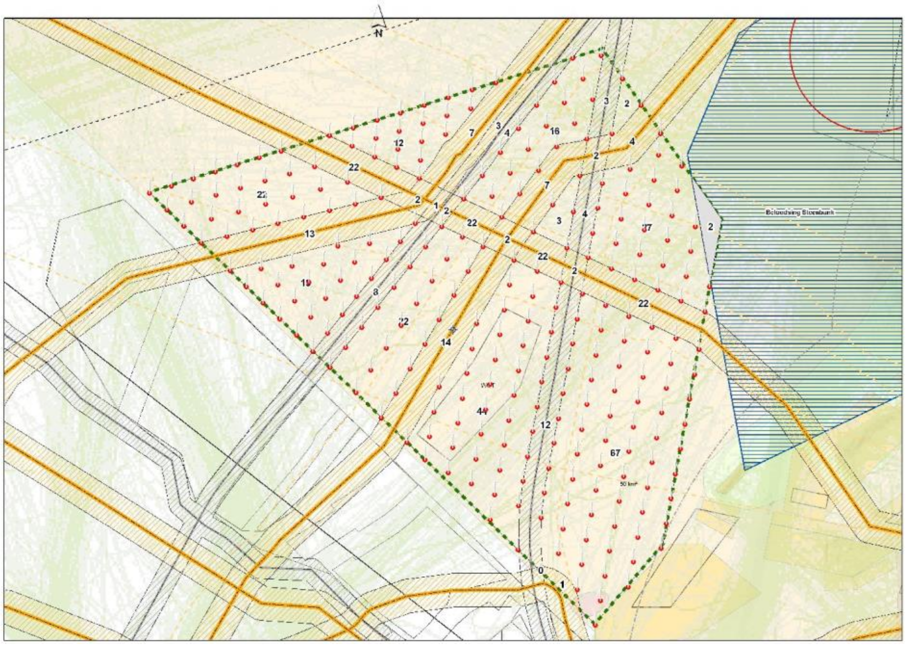

Figure 10: Layout of wind farm design 3.

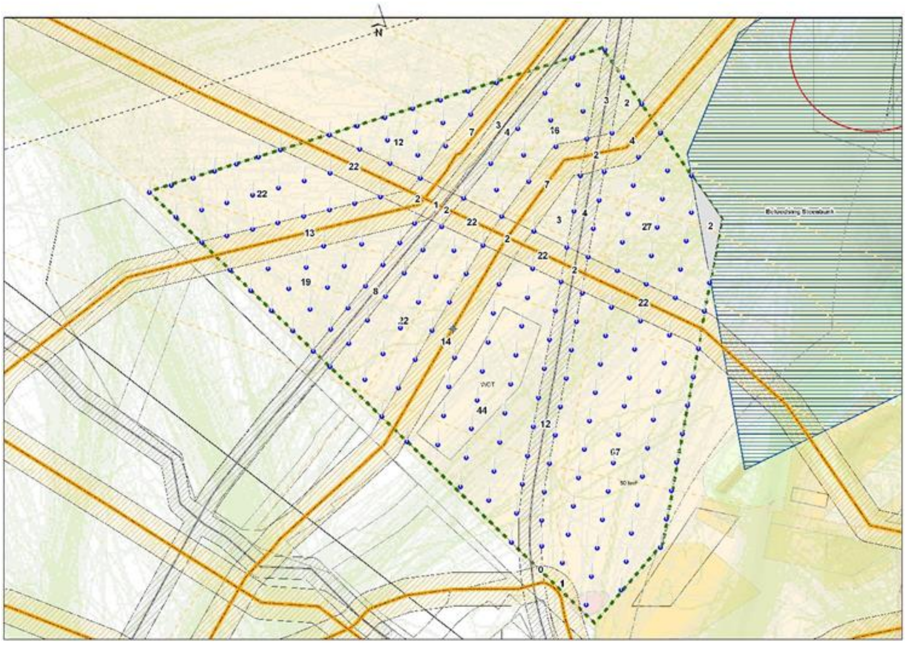

Figure 11: Layout of wind farm design 4.

2.3 Results

The energy yield analysis performed with FarmFlow predicted for each wind turbine the power, at the low voltage side of the wind turbine transformer, for all considered wind speed intervals and wind direction intervals. These results are combined with the wind speed and direction distribution given in section 2.1, resulting in the annual yield, capacity factor[3] and wind farm efficiency. These results are processed in such a way as shown in the graphs below, the annual yield, the capacity factor and farm efficiency for the four wind farm designs and for each parcel. It is assumed that the availability of the wind turbines is 100%, so no down time due to O&M or anything else.

An analysis with comparing the results using a wind speed distribution as if there are no wind farms on the Belgian side of the border results in an additional energy yield of approximately 4%.

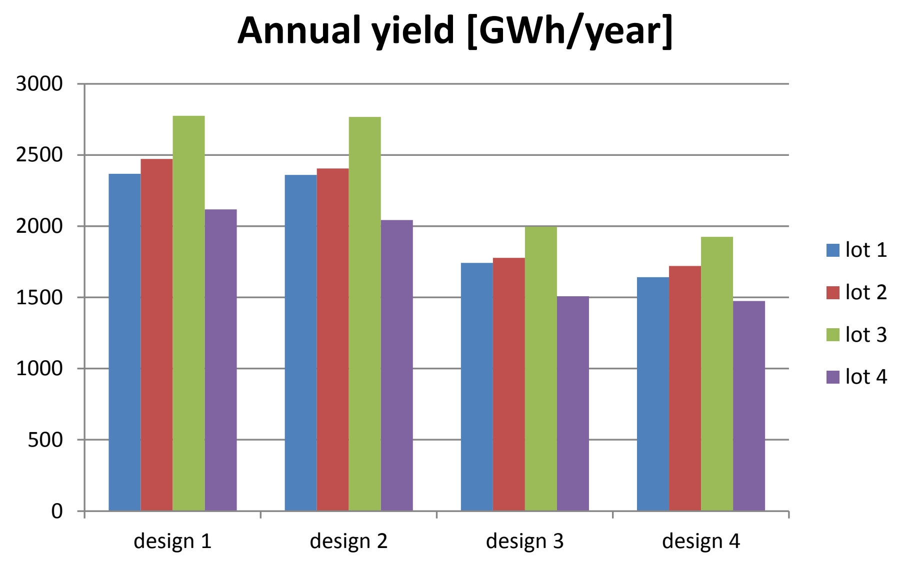

Figure 12: Annual yield at the four different parcels (lots) for four different designs.

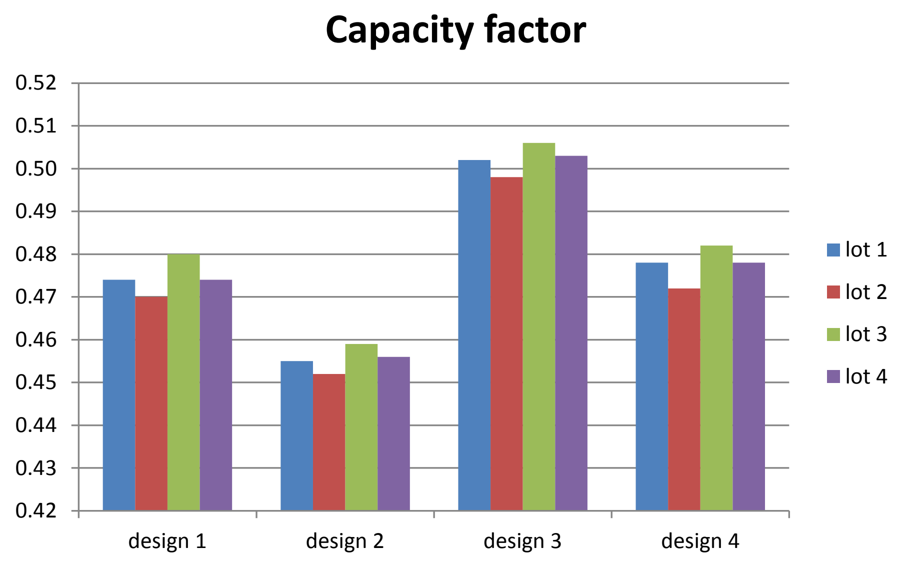

Figure 13: Capacity factors of the four different wind farm designs and parcels (lots)

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[3] The capacity factor is the ratio between the annual average power and the nominal power

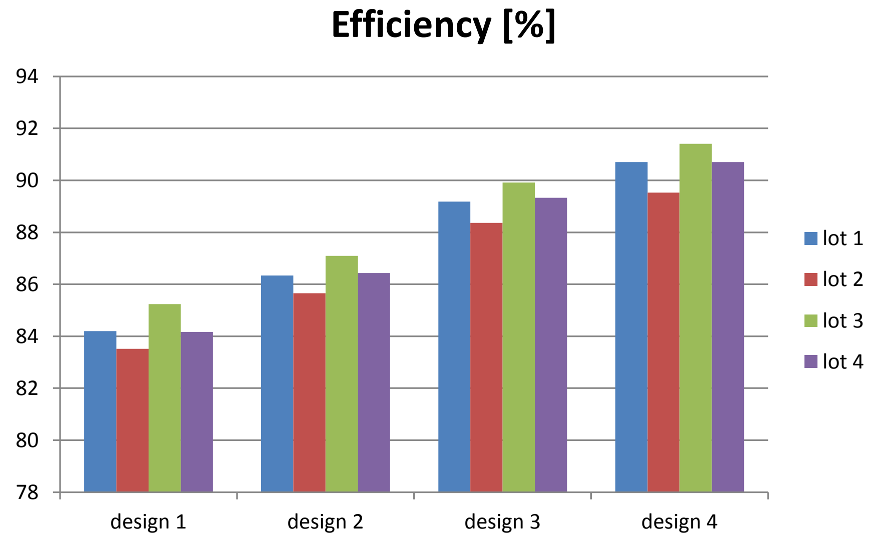


Figure 14: Efficiency of the four different wind farm designs and parcels (lots).

2.4 Discussion

The results of the created designs show that the used selection of the parcels results in nearly equal capacity factors and wind farm efficiencies. The yield between the conceptual designs differs mainly due to difference in nominal power of the different concepts

The differences between the parcels in capacity factor or wind farm efficiency are small. Within each conceptual design the performance of the different parcels are quite close to each other. Differences are in the order of 0.01 of the capacity factor.

The wind farm (wake) analyses for the different conceptual wind farms designs shows that the capacity factor for the designs with a low WF PD is substantially higher than the design with a high WF PD. This is also according to expectations.

The differences in capacity factor between the different wind farm power densities is approximately 5,5% in capacity factor or in the order of 6% difference in yield per wind turbine. The difference between the two wind turbine power densities shows that the capacity factor of the wind turbine concept with a low WT PD is slightly more than 2% higher compared to the high WT PD.

The reduction in energy yield due to the Belgian wind farms of 4% is actually substantially less than anticipated at forehand.
Several reasons can be thought of why this is the case, e.g.:

- ✓ the reduction of wind speed estimated is to optimistic due to the fact that the effect is determined based on the analysis of a small array of wind turbines.
- ✓ It could be due to the fact that modern wind turbines reach their rated power at lower wind speeds than in the past.

The influence of wind farms on each other is not yet well investigated.

3

The Electrical systems design

3.1 Introduction

For each of the four selected wind farm layouts a cable routing has been designed with either two or three 700MW substations at suitable locations in the farm.

The evaluations of the electrical designs result in estimated cable investment costs and a calculation of the electrical losses in the collection grid. The results of the aerodynamic simulations of FARMFLOW have been used as inputs.

This section describes the approach and main assumptions and of the design and the evaluation, followed by the results.

3.2 Approach

For the basic electrical design of the wind farm layouts the following assumptions have been made, mainly for reasons of the available time and planned effort:

- ✓ A single array cable type has been chosen for the whole wind farm, which is a 3-core XLPE cable, rated 30kV, 40 MVA, with a copper conductor of 630 mm^2.
- ✓ For each cable connection the length has been calculated as the shortest distance plus 10%.
- ✓ The cable failure rate has been chosen as 0.08 per year per 100km and a repair time of 1500 hours.

- ✓ A sound choice for the substation locations and the array cables has been made in order to limit the total cable length as well as cable crossings with existing infrastructure.
- ✓ The number of connected wind turbines on a string has been chosen such that the maximum current in the section to the substation approximately matches the cable rating. An exact match with the cable power rating is not required, because given the abovementioned cable specifications and electrical properties, suppliers provide cables with somewhat higher power ratings.
- ✓ The numbers of wind turbines and strings has been distributed evenly over the substations. The layouts with high Wind Farm power density (9 MW/km^2) contain three 700MW substations and those with low Wind Farm power density (6 MW/km^2) two.
- ✓ The costs and losses of the substations have not been included. The cost and losses of the medium voltage cables to the substation have been included.
- ✓ The cost of the connections of the wind turbines are assumed to be part of the wind turbine installation cost.
- ✓ The costs and unavailability of the wind turbines have not been included.

The Levelised Transport Cost (LTC) is determined using the following assumptions:
- ✓ Investment costs only
- ✓ 20 year lifetime, constant production over the years
- ✓ 7% interest rate
- ✓ 2% inflation

3.3 Results

The presented results are based on simulations in the ECN models EE-FARM and FARMFLOW and are presented in a relative way where the option with the per group of wind turbine strings connected to a single substation.

Figure 15shows the investments costs in the cables between wind turbines and platform for each of the four different wind farm layouts. As expected, for the cases with the same power density (MW/km^2), the lower the capacity per wind turbine, the longer the total cable length will be, and therefore the higher the total cable costs. For the two low density lay-outs at the right hand side, the total installed wind capacity is 33% lower. This results in lower total cable cost for the two low density lay-outs. But per MW of installed wind capacity the cable costs will be higher for the two low-WF PD lay-outs.

Figure 16shows the total cable distances in km for each of the four lay-outs. A distinction has been made between cables in between wind turbines (shown in blue), and from the last wind turbine to the platform.

Figure 17 Shows the nett energy production where the designs with the higher wind farm power densities produce more the most energy.

Figure 18 shows the losses of each design in a % of the total electrical yield produced by the wind turbines.

Figure 19 shows the relative Total Levelised Cost difference.

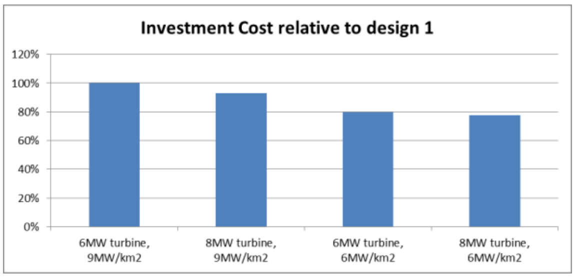


Figure 15: Investment costs in the cables between wind turbines and platform

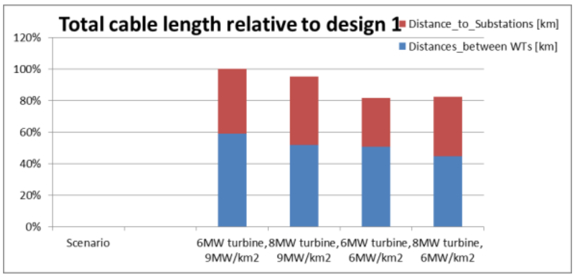


Figure 16: Cable distances

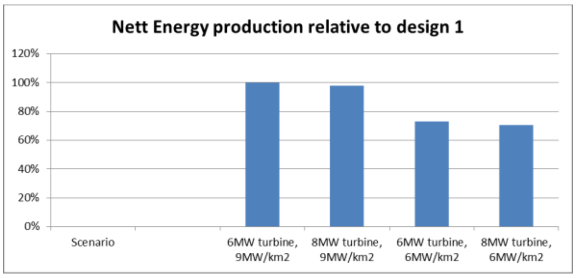


Figure 17: Net energy production in

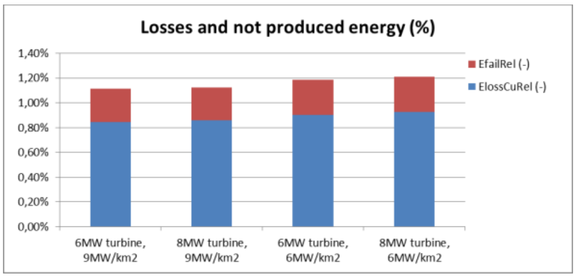


Figure 18: Electrical losses cable failure losses as % of energy yield

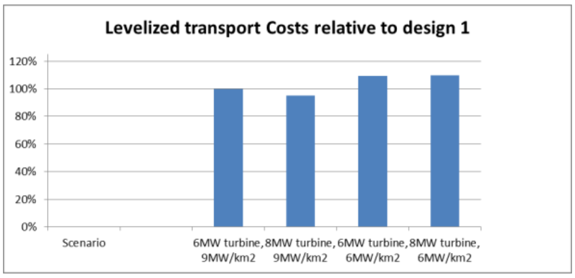


Figure 19: The Levelised transport cost

3.4 Discussion

On the basis of the present analysis it is difficult to make a clear statement which design is more efficient. Also due to the fact that only the cable cost and losses are taken into account the cost of the electrical system inside the wind farm is relatively low compared to the cost of a kWh generated by wind offshore, approximately € 4/MWh, see Appendix C .

However the results are in line with the expectation that the cost increase for the low WF PD designs and low WT PD wind turbines, contrary to the wind farm array efficiencies. A proper, integrated analysis can make clear what the optimal solution is.

4

Discussion

The results of the wind farm wake analyses and the results of the electrical system are contradictory, which was expected. A lower wind farm power density will result in lower wind farm wake losses but due to the larger distances between the wind turbines in a low WF PD design the cost of the electrical system and the losses in the electrical system go up. In a more detailed analysis, using real wind turbine models and all cost components and performance data into account, an optimum solution can be determined.

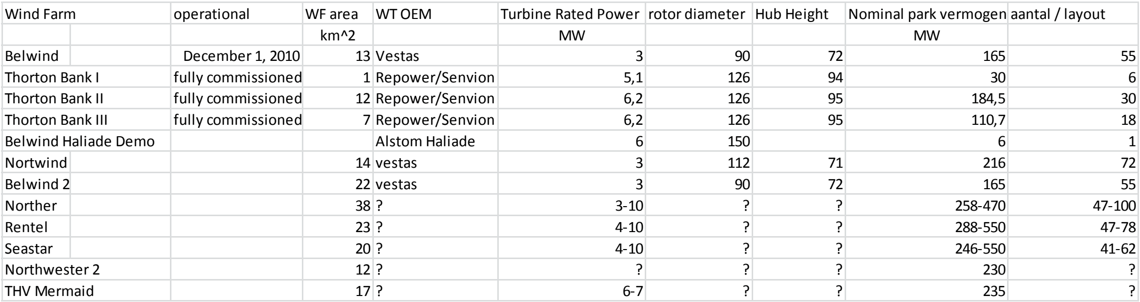
Due to the limited cost components taken into account for the electrical system study and the chosen concept of a modular hub @ sea the influence of the electrical system cost is relatively low compared to the total cost.

Overall should be mentioned that due to the limited scope of this quick scan study the differences for the four different conceptual designs are smaller than to be expected when a more detailed study will be performed.

Appendix A. The wind farms on the Belgian side of the border

On the Belgian side of the border 12 wind farms are planned of which 4 are already operational today.

Table 5 Data of the wind farms on the Belgian side of the border, (http://http://www.4coffshore.com) .



Wind Farm	operational	WF area	WT OEM	Turbine Rated Power	rotor diameter	Hub Height	Nominal park vermogen	aantal / layout
		km^2		MW			MW	
Belwind	December 1, 2010	13	Vestas	3	90	72	165	55
Thorton Bank I	fully commissioned	1	Repower/Senvion	5,1	126	94	30	6
Thorton Bank II	fully commissioned	12	Repower/Senvion	6,2	126	95	184,5	30
Thorton Bank III	fully commissioned	7	Repower/Senvion	6,2	126	95	110,7	18
Belwind Haliade Demo			Alstom Haliade	6	150		6	1
Nortwind		14	vestas	3	112	71	216	72
Belwind 2		22	vestas	3	90	72	165	55
Norther		38	?	3-10	?	?	258-470	47-100
Rentel		23	?	4-10	?	?	288-550	47-78
Seastar		20	?	4-10	?	?	246-550	41-62
Northwester 2		12	?	?	?	?	230	?
THV Mermaid		17	?	6-7	?	?	235	?

Figure 20 The wind farms on the Belgian side, copied from http://http://www.4coffshore.com

Appendix B. The characteristics of the wind turbines

The wind turbine models used in the FarmFlow analysis have the following power and axial force curve

Table 6: The wind turbine power curve and axial force coefficient

U	6 MW 154 m wind turbine		8 MW 164 m wind turbine	
[m/s]	P [kW]	C_T [-]	P [kW]	C_T [-]
3	0	0	0	0
4	268	0.858	130	0.816
5	585	0.858	580	0.775
6	1058	0.858	1120	0.78
7	1710	0.857	1860	0.782
8	2573	0.858	2860	0.782
9	3673	0.857	4080	0.783
10	4850	0.804	5600	0.783
11	5665	0.607	7100	0.783
12	5945	0.418	7860	0.523
13	5993	0.316	7950	0.388
14	6000	0.248	7980	0.302
15	6000	0.201	7995	0.241
16	6000	0.165	8000	0.197
17	6000	0.138	8000	0.164
18	6000	0.117	8000	0.138
19	6000	0.100	8000	0.118
20	6000	0.087	8000	0.102
21	6000	0.076	8000	0.088
22	6000	0.067	8000	0.078
23	6000	0.06	8000	0.069
24	6000	0.053	8000	0.061
25	6000	0.048	8000	0.055

Appendix C. Detailed results of the analysis of the electrical system

The presented results are based on simulations in the ECN models EE-FARM-2 and FARM-FLOW and are presented per group of wind turbine strings connected to a single substation.

Table 7 to **Table 10** show the key outputs of the simulations, from left to right: The investment costs in the cables including cable laying and the transformers in the wind turbine in M€. The costs do not include Net generation of the wind turbines in GWh/year. Electricity losses in the cables connecting the wind turbines with the platforms (both in GWh/year and in % of generation). The column Efail contains electricity generated by the wind turbines which could not be transported to the platform due to cable failure (both in GWh/year and in % of generation). The last column shows Levelized Transport Cost, based on the investment costs of the cables (€/MWh).

Table 7: Layout with 6MW turbines and power density of 9 MW/km^2

6MW WT, 9MW/km^2	Invest vest-ment	Efarm nett	E_{loss}	E_{loss}	E_{fail}	E_{fail}	LTC
Node	**(M€)**	**(GWh/y)**	**(GWh/y)**	**(-)**	**(GWh/y)**	**(-)**	**(€/MWh)**
Total_Subs1	142	3171	24	0,8%	8	0,3%	3,6
Total_Subs2	174	3577	32	0,9%	10	0,3%	3,9
Total_Subs3	136	2723	24	0,9%	7	0,3%	4,0
Total	**453**	**9471**	**80**	**0,8%**	**26**	**0,3%**	**3,8**

Table 8: Layout with 8MW turbines and power density of 9 MW/km^2

8MW WT, 9MW/km^2	Investment	Efarm nett	E_{loss}	E_{loss}	E_{fail}	E_{fail}	LTC
Node	**(M€)**	**(GWh/y)**	**(GWh/y)**	**(-)**	**(GWh/y)**	**(-)**	**(€/MWh)**
Total_Subs1	132	3063	25	0,8%	8	0,3%	3,4
Total_Subs2	138	3117	27	0,9%	8	0,3%	3,5
Total_Subs3	150	3088	28	0,9%	9	0,3%	3,9
Total	**420**	**9268**	**80**	**0,9%**	**25**	**0,3%**	**3,6**

Table 9: Layout with 6MW turbines and power density of 6 MW/km^2

6MW WT, 6MW/km^2	Investment	Efarm nett	E_{loss}	E_{loss}	E_{fail}	E_{fail}	LTC
Node	**(M€)**	**(GWh/y)**	**(GWh/y)**	**(-)**	**(GWh/y)**	**(-)**	**(€/MWh)**
Total_Subs1	204	3802	34	0,9%	11	0,3%	4,3
Total_Subs3	157	3123	28	0,9%	9	0,3%	4,0
Total	**361**	**6925**	**62**	**0,9%**	**20**	**0,3%**	**4,1**

Table 10: Layout with 8MW turbines and power density of 6 MW/km^2

8MW WT, 6MW/km^2	Investment	Efarm nett	E_{loss}	E_{loss}	E_{fail}	E_{fail}	LTC
Node	**(M€)**	**(GWh/y)**	**(GWh/y)**	**(-)**	**(GWh/y)**	**(-)**	**(€/MWh)**
Total_Subs1	174	3505	31	0,9%	10	0,3%	4,0
Total_Subs3	176	3188	31	1,0%	9	0,3%	4,4
Total	**351**	**6693**	**62**	**0,9%**	**19**	**0,3%**	**4,2**

Appendix D. FARMFLOW

For the accurate prediction of wind turbine wake effects in (large) offshore wind farms, ECN has developed the software tool . FARMFLOW calculates the average velocities and turbulence levels inside a wind farm. A boundary layer model is used for the calculation of the free stream wind speed and can be used for assessments for different atmospheric stability conditions. Currently FarmFlow is extended to include an assessment of mechanical loads on the wind turbines. A coupling with the design code for electrical infrastructure EE-FARM, see Appendix E, enables an integrated approach toward the design of offshore wind power plants.

For the validation of FARMFLOW, a large amount of accurate experimental data from Nordex N80 2.5MW wind turbines from ECN Wind Turbine test station Wieringermeer (EWTW) has been used. Additionally, experimental data from three large offshore wind farms have been applied.

The calculated wake velocity deficits and turbulence intensities agree very well with experimental data for all wind speeds and ambient turbulence intensities. Excellent agreement between calculated and measured turbine performance is found. FARMFLOW tends to slightly overestimate the generated turbulence intensity.

The wake model in FARMFLOW is based on a 3D parabolised Navier-Stokes code, using a k-epsilon turbulence model to account for turbulent processes in the wake. The ambient flow is modelled in accordance with the method of Panofsky and Dutton[4]. The free stream wind as a function of height is calculated for a prescribed ambient turbulence intensity and Monin-Obukhov length, which takes the atmospheric stability into account.

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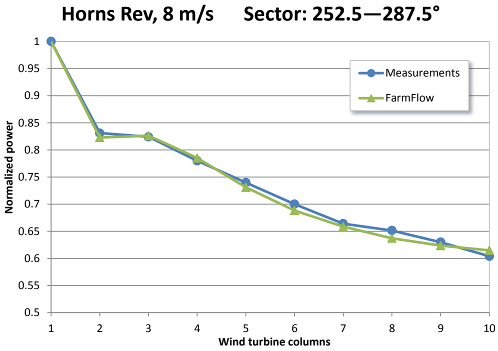
[4] Atmospheric turbulence : models and methods for engineering applications / Hans A. Panofsky, John A. Dutton



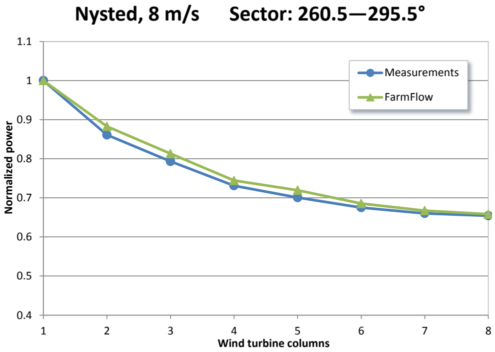


Figure 21: Normalized power as a function of column number in the Horns Rev wind farm in ambient wind speeds of 8.0 ± 0.5 m/s aligned parallel to the rows ± 17.5°.

Figure 22: Normalized power as a function of column number in the Nysted wind farm in ambient wind speeds of 8.0 ± 0.5 m/s aligned parallel to the rows ± 17.5°.

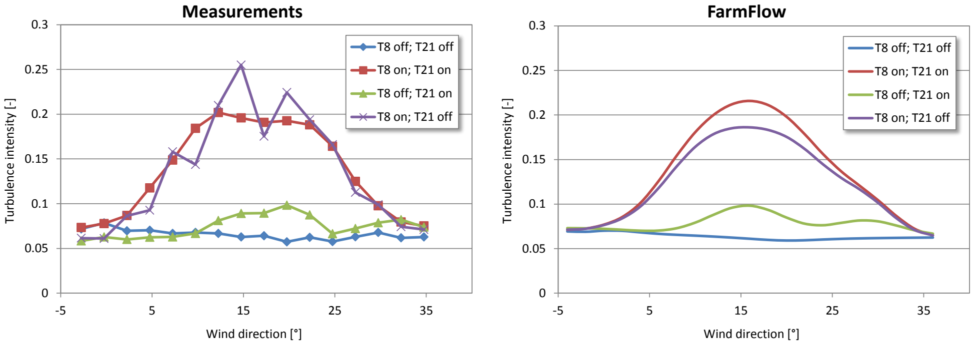


Figure 23: Measured (left) and calculated (right) turbulence intensities at hub height as a function of the wind direction. The graphs show Weibull averaged turbulence intensities of all combinations of operating (on) and not operating (off) turbines for ambient wind speeds between 5 and 11.5 m/s. (data from OWEZ wind farm)

Appendix E. EE-FARM

EE-FARM has been developed to study and optimise the electrical performance of wind farms. The program is used to determine the energy production, electrical losses, component failure losses and the price of the produced electric power of a wind farm. The program consists of a component library, a component database and a postprocessor. The component library contains steady state models of wind turbines, generators, transformers, AC and DC cables, PWM (pulse width modulated) and thyristor converters and of an inductor, statcom and chopper. The model is unique that in the calculations both DC and AC components can be combined
EE-FARM is programmed in MATLAB -Simulink. By using a component library, structured component parameters and a single bus signal to connect the different components in a wind farm, it is very easy for the user to build his specific wind farm model. After choosing the wind farm component blocks from the library and connecting the component blocks in Simulink, the parameters of all wind farm components are loaded by preparing a small MATLAB file that calls the database and selects the component data to be fed to individual components. Wind speed and wind direction data generated by a wind farm wake program, for instance FarmFlow, can be fed into the turbine blocks.

The EeFarm Model
EE-FARM calculates the voltage, current, active and reactive power of the main electrical components in a wind farm. The calculation starts at the turbines and proceeds in the direction of the high voltage grid. The AC component models are the well-known equivalent circuit diagrams for generators (induction, doubly fed and full converter), cables and transformers. For the PWM converter three different models representing the switching and conduction losses can be chosen. EE-FARM does not solve the load flow in the classical way because this would make it difficult to include DC components. Instead, it determines an average solution which is sufficiently accurate to determine the losses and the produced power. This is repeated for each wind speed bin of the turbine power curve. The average solution is sufficiently accurate due to the small voltage drops and the small voltage angle differences in a wind farm.
The results for each wind speed bin are combined with the wind speed distribution to determine the energy production and the price of the produced electric power.

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