Quick scan of the influence of the Borssele Wind Farms on the (planned) offshore wind farms in Belgium including losses for nearby Belgian Wind Farms.

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February 2015
ECN-E--15-015

Abstract

In this report the influence of a 1400 MW wind farm at the Borssele Zone on the energy production of the nearby Belgian wind farms is calculated with FARMFLOW. Next to that the analysis and predictions are listed of 6 different design options for the wind farms at the Borssele Wind Farm Zone. The 6 different wind farm designs vary in:

- ✓ nominal power, 700, 1400 and 2100 MW and
- ✓ two different wind turbines, one with a rated power of 6 MW with a rotor diameter of 154 m and one with a rated power of 8 MW with a rotor diameter of 164 m.

The Belgian offshore wind farms are modelled with the 8 MW wind turbine. The design is created on the basis of the publicly known data qua wind farm nominal power.

The predicted losses for the Belgian wind farms due to a 1400 MW wind farm on the Dutch Borssele zone is on average approximately 2.7%.

The 6 different designs at the Borssele Wind Farm Zone show capacity factors from 48% to 54% with wind farm wake losses between 14% to less than 4% depending on the size and turbine type.

The highest energy production predicted is approximately 2300 GWh

Contents

1

Introduction

In assignment of the ministry of Economic Affairs of the Netherlands, a quick scan study has been performed to predict the performance of planned and existing wind farms near Borssele on the Dutch as well as the Belgian side of the border.

The first subject calculated is to estimate the influence of the planned wind farms at the Borssele Wind Farm Zone on the power production of the wind farms build and planned at the Belgium side of the border. The information in the RVO report, see [1], is used to model the Belgian wind farms.

Next to that also the wind farm array wake effects and load factor or capacity factor are determined for two types of wind turbines and for 3 different lay-outs.

The work is a follow up of the work done in a previous assignment, the Quick Scan Wind Farm efficiencies of the Borssele location, see [2].

In the previous study, 4 different designs were made for the Borssele location

Table 1: The characteristics of the 4 wind farm designs created in [2]

Wind farm design	WT P_{rated} [MW]	rotor density [W/m^2]	wind farm power density [MW/km^2]	Number of WT's	Nominal Power Wind Farm [MW]
1	6	320	9	390	2340
2	8	380	9	300	2400
3	6	320	6	266	1596
4	8	380	6	200	1600

In this study, task two is to redesign the previous 4 designs to match the exact, i.e. closest possible, to 1400 and 2100 MW and next to that also design wind farms for the complete Borssele zone to a nominal power of 700 MW for both wind turbine types.

The following tasks are performed to determine these effects:

Task 1 a. Design a reference wind farm for the Belgian wind farms.

Task 1 b. Calculate the wind farm performances for the Belgian Wind Farms and determine the array losses

Task 1 c. Calculate the wind farm performance assuming the Borssele zone is fully developed and operational based on the characteristics of design 3 of the previous study, i.e. the 6 MW wind turbine with the low power density but with less wind turbines to have a nominal wind power for the 4 sites of 1400 MW.

Task 2 a. Create new wind farm designs for the Borssele zone wind farms but now based on 1400 and 2100 MW or as close as possible using 6 and 8 MW wind turbines.

Task 2 b. Calculate the wind farm efficiencies using the same wind rose as used in the analysis performed in [2].

Task 2 c. Create new designs for the Borssele zone based on a total installed wind power of 700 MW or 175 MW for each site also using the 6 as well as the 8 MW design.

Task 2 d. Calculate the wind farm efficiencies of the 700 MW designs using the same wind rose as used in2 Task 2 b

The results of the designs and calculations can be found in this report.

1.1 The wind farms designs

Dutch wind farms

Due to the fact that the wind farms on the Dutch side are still in pre-tender phase and consequently not yet designed, the designs used in the analysis are based on the designs used in the previous study to determine the effect of the Belgian Wind Farms on the wind farms planned at the Borssele zone, see [2]. In total 6 wind farm designs have been made, using two different wind turbine models and for 3 different rated power configurations, 700, 1400 and 2100 MW nominal power. The changes, with respect to the ones used in [2] will be that each of the 4 wind farm sites within the Borssele Zone will have a nominal power close to 175 MW, 350 MW and 525 MW totalling the nominal power for the Borssele Wind Farm Zone to 700, 1400 and 2100 MW.

Belgian wind farms

The Belgian wind farms are modelled on the public available data in [1], see **Table 2**, from the website www.4cOffshore.com. For some of the Belgian offshore wind farms, it is not yet known which wind turbines type will be used and what the lay-out will be. For this reason it is decided to use a conceptual design that makes use of the average power density, i.e. number of MW/km^2, as given in [1] and excluding the cable/pipeline areas for the locations of wind turbines.

Table 2: The Belgian offshore wind farms information on the www.4coffshore.com website.

Project	Commission date/ u.c	Wind Farm Area	P_{rated} WT	D_{rotor}	H_{hub}	Nominal WF power	# WT's
		Km^2	MW	m	m	MW	
Belwind	2010 - 12	13	3	90	72	165	55
Belwind 2 Haliade pilot	2013 - 11		6	150		6	1
Belwind 2	u.c.	22	3	90	72	165	55
C-Power I / Thorton Bank I	2009 - 06	1	5,1	126	94	30	6
C-Power II / Thorton Bank II	2012 - 07	12	6,2	126	95	184,5	30
Cpower III / Thorton Bank III	2013 - 07	7	6,2	126	95	110,7	18
Northwind	2014 - 06	14	3	112	71	216	72
Norther	u.c.	38	3-10			258-470	47-100
Rentel	uc	23	4-10			288-550	47-78
Seastar	u.c	20	4-10			246-540	41-62
Northwester 2	u.c	12	3-10			224/296	20-80
THV Mermaid	u.c	17	3-10			320	24-80

*uc = Under construction

Figure 1: The operational and planned wind farms on the Belgian side of the Border (http://www.4coffshore.com)

1.2 The wind turbine models

For the Dutch wind farms two different wind turbines models are used, one with a rated power of 6 MW and one with a rated power of 8 MW. The rotor power density, i.e. the ratio of the rated power over the rotor area, was also different between the two wind turbines. The 6 MW design has a rotor power density of approximately 320 W/m^2 and the 8 MW model has a rotor power density of approx. 380 W/m^2. This resulted in an 8 MW wind turbine with a rotor diameter of 164 m and a 6 MW wind turbine with a rotor diameter of 154 m.

For the Belgian wind farms only the 8 MW wind turbine model is used with the high rotor power density of 380 W/m^2. The choice to model the Belgian wind farms only with the 8 MW model was made due to the fact that the average wind farm power density in the Belgian wind farms is relatively high, ~12 MW/km^2 and modelling it with the 6 MW wind turbine and the low rotor power density would result in wind farms with a small spacing between wind turbines resulting in high array losses.

The characteristics of the wind turbine models used in the analysis can be found in Appendix A.

1.3 The undisturbed wind rose at the Borssele Wind Farm Zone.

The wind conditions at the Borssele Wind Farm zone are based on a database of wind conditions maintained by ECN. A full period of 10 years, 2003 – 2013, has been used to derive the wind data. The derived wind rose has been used to predict the power production of the Belgian wind farms without the influence of the Dutch wind farms and with the influence of the Dutch wind farms to determine the additional losses for the Belgian Wind Farms due to the Dutch wind farms.

The wind rose at 105 m height is given in **Table 3**

Table 3: The Weibull data for 12 sectors at a height of 105 m.

	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	9.59	2.09	8.50	690.85
7	S	7.47	11.94	2.14	10.58	1301.53
8	SSW	13.34	12.95	2.41	11.48	1507.93
9	SWW	14.85	12.53	2.40	11.11	1370.28
10	W	10.50	11.46	2.19	10.15	1127.71
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	100	10.95	2.20	9.70	1005.20

1.4 The wind rose for the Borssele Wind Farm zone, including the effect of the Belgian wind farms.

For the second task the wind conditions at the Borssele wind farm zone are determined on the basis of the undisturbed wind rose, see previous paragraph, which is corrected to take the effect of the (planned) Belgian wind farms in account. This correction shows the lower wind speeds from the south due to the Belgian wind farms and an increase of the turbulence for winds coming from the south. The wind rose and turbulence rose are identical to the one used in the report [2].

Table 4: 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	Δ A	Weibull k	Wind speed	Δ V	Power density
	[%]	[m/s]	[m/s]		[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	-0.17	2.09	8.26	-0.24	634.33
7 SWW	7.47	11.10	-0.84	2.14	9.83	-0.75	1046.30
8 SSW	13.34	12.05	-0.90	2.41	10.68	-0.80	1215.50
9 SWW	14.85	11.66	-0.87	2.40	10.34	-0.77	1104.80
10 W	10.50	10.97	-0.49	2.19	9.72	-0.43	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	**100**	**10.57**	**-0.38**	**2.20**	**9.37**	**-0.43**	**890.35**

1.5 The wind farm wake analysis

The wind farm wake analysis is performed with FARMFLOW. The FARMFLOW model is developed by ECN to predict the wind turbine wake effects of offshore wind farms. The tool comprises a wake model that has been verified with measurements and compared to other models in numerous (benchmark) projects. See Appendix B for a more extensive description of the model and the verification documents.

1.6 The results

The results of the analysis are the energy yield of the Belgian Wind Farms without and with the Dutch wind farms present. The difference between the yields of the two situations is the additional energy losses due to the presence of the Dutch wind farms.

Next to that also the energy yields of the 6 different designs for the Borssele zone are listed. In each design the presence of all the Belgian offshore wind farms close to the Borssele zone are assumed in the same way as in the previous study.

2

The wind farm designs

2.1 The Belgian offshore wind farms

The Belgian wind farms are modelled on the basis of the limited information that is publicly available. Due to the fact that the average power density of the Belgian wind farms is rather high, ~ 12 MW/km^2, it is decided to use only the 8 MW wind turbine model with a relatively high power density of 380 W/m^2 to reduce the internal wake effects inside the Belgian wind farms.

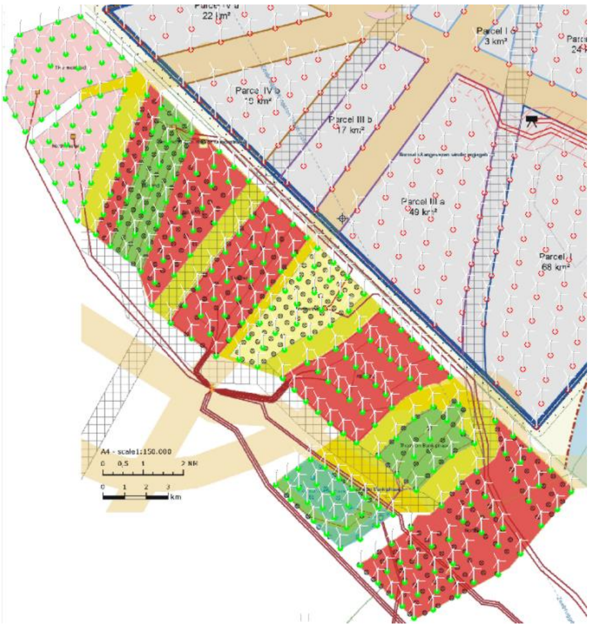

Figure 2: The lay out of the Belgian Wind Farms

The wind farms are modelled with in total 281, 8 MW wind turbines with a rotor diameter of 164 m. The total nominal power as modelled is 2248 MW.

2.2 The Dutch offshore wind farms at the Borssele zone

Six different wind farms designs are created at the Borssele zone, where the total nominal power of the zone varies between approx. 700 MW to 2100 MW, see **Table 5**

Table 5: The nominal power of the Borssele location wind farm and number of wind turbines.

Design	Number of WT [-]	P_{rated} WT [MW]	Nominal power [MW]
1	350	6	2100
2	262	8	2096
3	233	6	1398
4	175	8	1400
5	117	6	702
6	88	8	704

The Borssele zone is divided into 4 wind farm sites; the numbering is shown in **Figure 3**

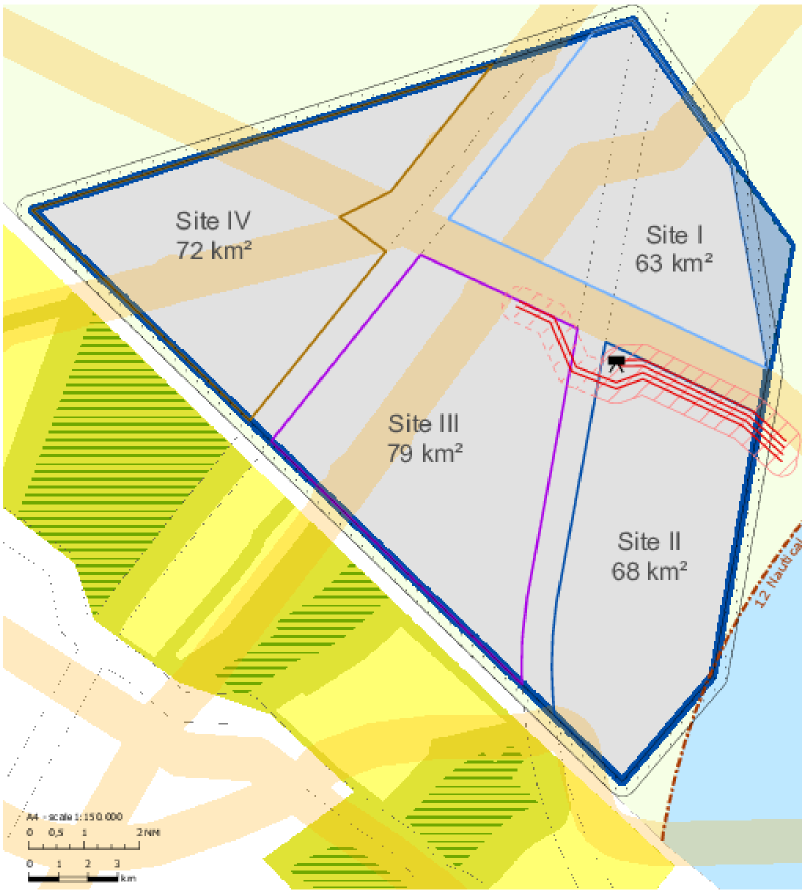

Figure 3: The Borssele wind farm zone divided into four wind farm sites.

The six designs are shown in the **Figure 4**. a) – f) As shown, the cable and pipeline areas are excluded from the design space.

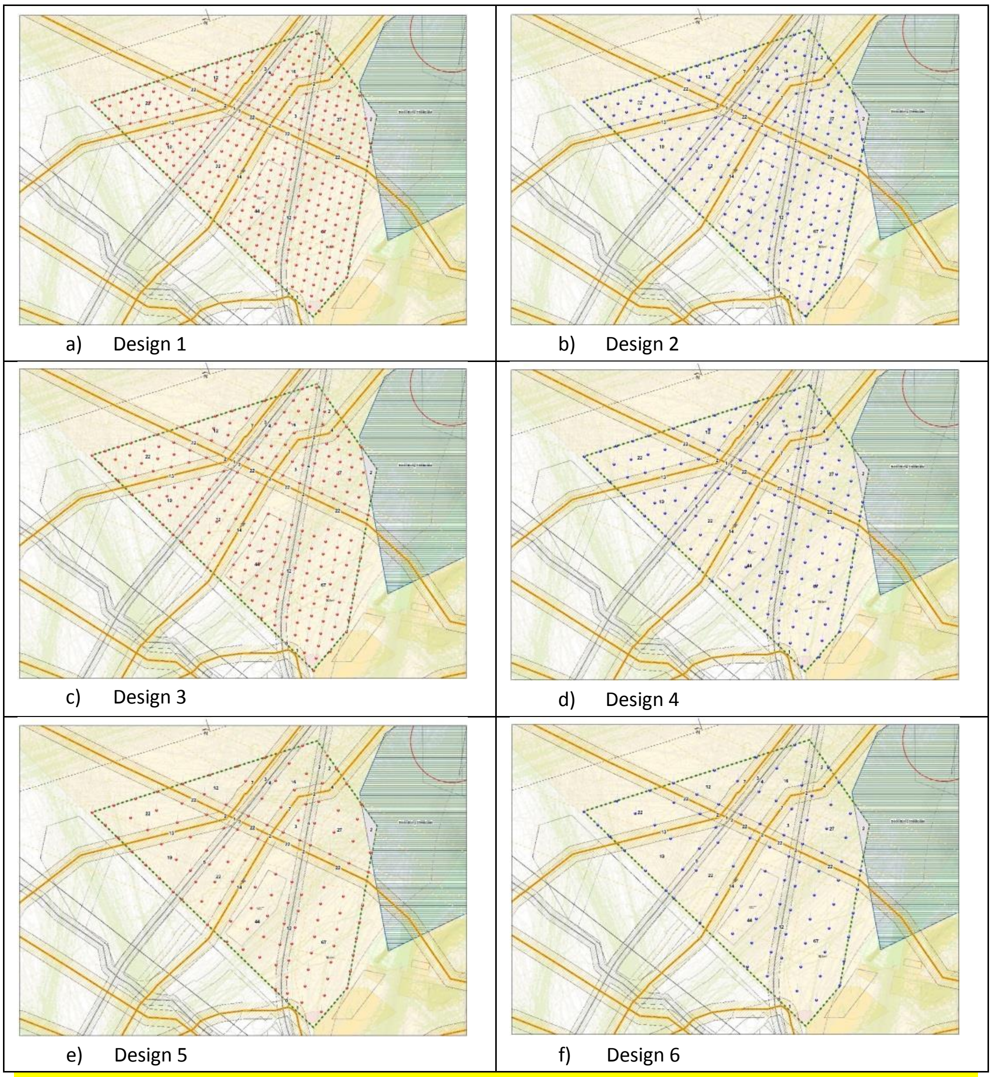

Figure 4: The six wind farms designs at the Borssele zone

For each design and each wind farm site within the Borssele zone the number of wind turbines and the rated power has been determined. Due to the fact that power is always a multiple of 6 or 8 MW it will not be possible to get exactly to the requested nominal power of 175, 350 and 525 MW per site.

Table 6: Rated power and number of wind turbines per site for each wind farm design.

Design	Site I		Site II		Site III		Site IV		total	
	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]	# of WT's	$P_{nominal}$ [MW]	# of	$P_{nominal}$ [MW]
1	86	516	87	522	89	534	88	528	264	2100
2	65	520	66	528	66	528	65	520	228	2096
3	58	348	58	348	58	348	59	354	175	1398
4	43	344	44	352	44	352	44	352	132	1400
5	29	174	29	174	30	180	29	174	88	702
6	22	176	22	176	22	176	22	176	66	704

3

The results

3.1 The yield reduction for the Belgian wind farms due to the Borssele zone wind farms.

The yield of the Belgian offshore wind farms has been calculated with FARMFLOW with and without the presence of the wind farms in the Dutch Borssele Wind Farm zone. An example of the analysis is show in figure below indicating the number of wake, the length of the wake and the number of wind turbines in a wake analysis for a single wind direction and wind speed.

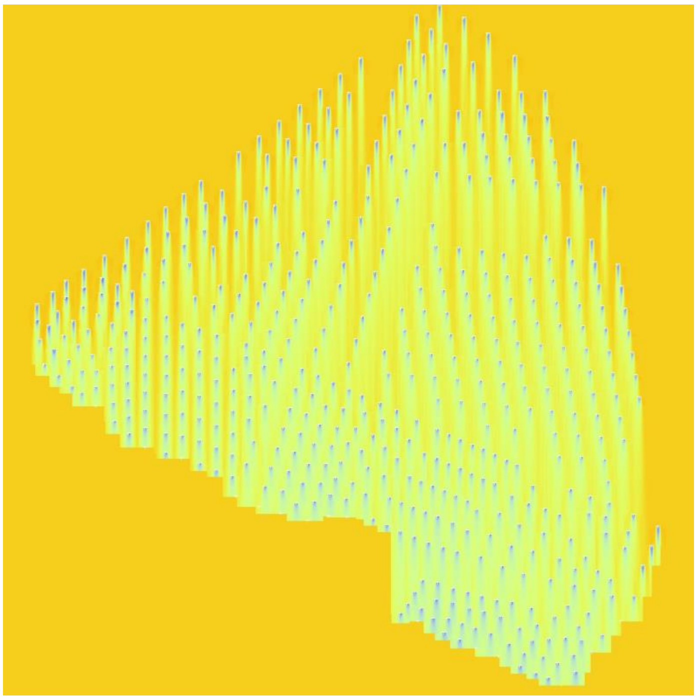

Figure 5:
A graphic representation of the wake analysis performed for one wind speed and one wind direction (here wind coming from the North)

The analysis with the wind turbines in the Borssele Wind Farm zone are based on design 3, i.e. the wind farms with a nominal power of 1400 MW based on 6MW wind turbines.

Design 3 is selected for this comparison due to the fact that at present the 1400 MW options is most likely option and for conservative reasons the option with the 6 MW wind turbines reduces the wind speeds for the Belgian wind farms more than the 8 MW wind turbine.

The yield of the Belgian Off-shore wind farms is on average reduced by 2,7% due to the wind farms in the Borssele Wind Farm Zone.

Table 7: The characteristics of the Belgian wind farms, used in the analysis, and the results of the FARMFLOW analysis.

Site	# WT	Nominal Power	Yield excl. BWF	Cap. Fac.	Yield Incl. BWF	Cap. Fac.	Add. loss
	[-]	MW	GWh	[-]	GWh	[-]	[-]
Belwind	48	384	1589,3	0,4725	1535,8	0,4566	3,36%
Seastar	31	248	1024,2	0,4714	989,9	0,4556	3,35%
Northwind	24	192	782,2	0,4650	754,1	0,4484	3,59%
Rentel	36	288	1185,8	0,4700	1143,1	0,4531	3,60%
Thornton Bank	39	312	1288,2	0,4713	1262,2	0,4618	2,01%
Norther	48	384	1614,6	0,4800	1584,3	0,4710	1,88%
Mermaid	31	248	1050,6	0,4836	1025,8	0,4722	2,36%
Northwester 2	24	192	793,4	0,4717	778,0	0,4626	1,94%
All	**281**	2248	9328,1	0,4737	9073,2	0,4607	2,73%

The average reduction of electricity production due to Borssele is approximately 2.7%.

3.2 The yield, array efficiencies and capacity factors at the Borssele zone

The yield of the Borssele zone sites has been calculated with FARMFLOW based on the same wind rose as was used in the previous study [2]. For each site with the Borssele zone the energy yield, the capacity factor and the wind farm efficiency has been determined. The results are shown in **Tables 8** - **10** and in the **Figure 6** – **Figure 8**.

Table 8 and **Figure 6** show the energy production for the site I – IV of the Borssele Wind Farm Zone for each of the six designs.

Table 9 and **Figure 7** show the capacity factor of the wind farm, i.e. the ratio of the predicted electricity production divided by the electricity production assuming that the farm is producing always its rated power.

Table 10 and **Figure 8** show the wake losses, the difference in electricity production for a solitary wind turbine on the basis of the wind rose and the calculated electricity production of the complete wind farm divided by the number of wind turbines in the wind farm.

Table 8: The calculated energy yield [GWh/year] for all six designs and for each site.

	Design					
Site	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
	2100 MW		1400 MW		700 MW	
	6MW	8MW	6MW	8MW	6MW	8MW
I	2178,25	2098,63	1549,12	1452,68	814,26	776,50
II	2227,14	2144,04	1548,78	1492,29	811,53	776,15
III	2273,98	2143,85	1544,21	1483,11	836,00	773,14
IV	2304,43	2172,24	1607,88	1521,14	822,16	786,45
total	8983,80	8558,75	6249,97	5949,23	3283,96	3112,24

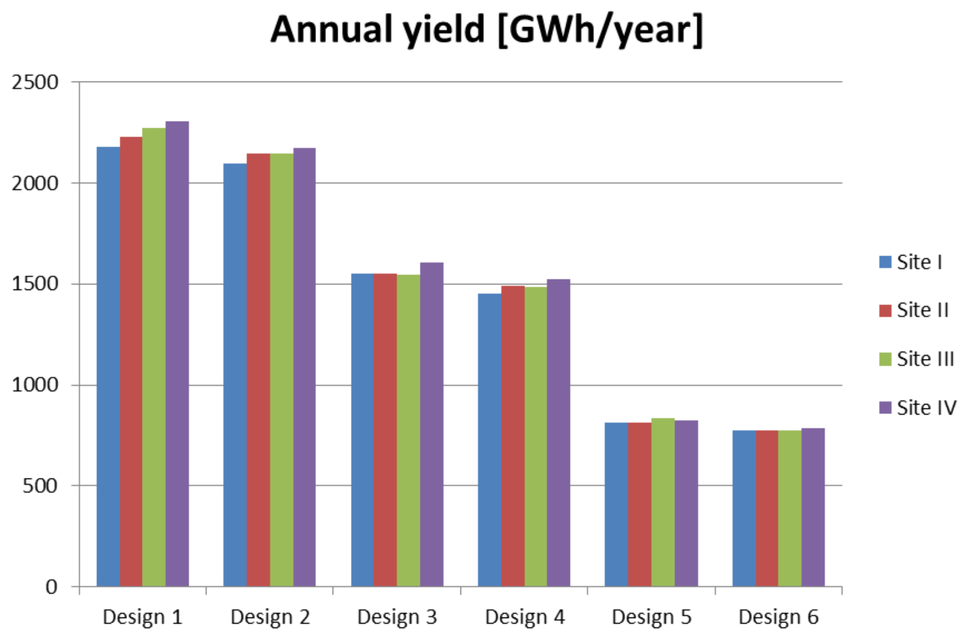

Figure 6: Annual yield at the four different sites for six different designs.

Table 9: The capacity factor for all six designs and for each site

	Design					
Site	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
	2100 MW		1400 MW		700 MW	
	6MW	8MW	6MW	8MW	6MW	8MW
I	0,482	0,461	0,508	0,482	0,534	0,504
II	0,487	0,464	0,508	0,484	0,532	0,503
III	0,486	0,464	0,506	0,481	0,530	0,501
IV	0,498	0,477	0,519	0,493	0,540	0,510
Average	0,488	0,466	0,510	0,485	0,534	0,505

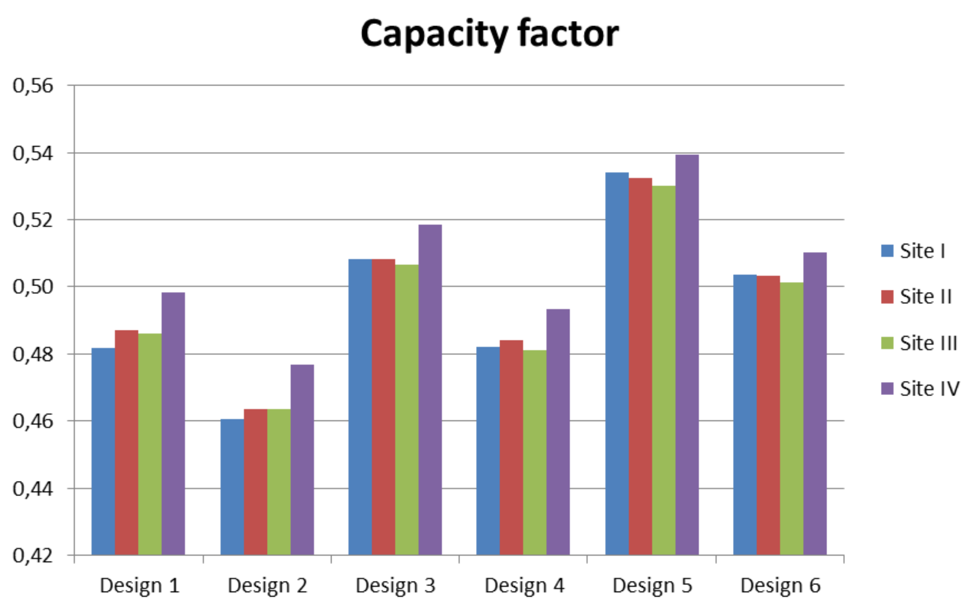

Figure 7: Capacity factors of the six different wind farm designs and four sites.

Table 10: The wind farm efficiency for all six designs and for each site.

	Design					
Site	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
	2100 MW		1400 MW		700 MW	
	6MW	8MW	6MW	8MW	6MW	8MW
I	85,9	87,2	90,5	91,2	95,2	95,3
II	86,8	87,7	90,5	91,6	94,9	95,3
III	86,6	87,7	90,2	91,0	94,5	94,9
IV	88,8	90,2	92,4	93,4	96,1	96,5
Average	87,0	88,2	90,9	91,8	95,1	95,5

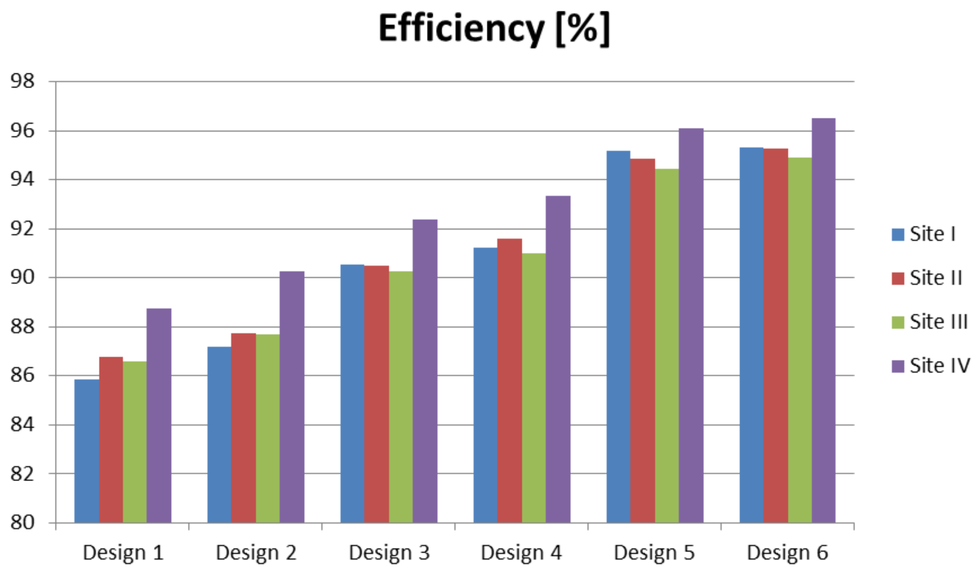

Figure 8: Efficiency of the six different wind farm designs and each site.

4 References

[1] Borssele Wind Farm Zone, project & site description. public, Netherlands Enterprise Agency, December 2014.

[2] B.H. Bulder, E.T.G. Bot, W. Wiggelinkhuizen, and F. Nieuwenhuizen. Quick scan wind farm efficiencies of the Borssele location. Technical Report ECN-E–14-050, ECN, June 2014.

Appendix A. The characteristics of the wind turbines

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

Table 11: The wind turbine power curve and axial force coefficient

	6 MW 154 m wind turbine		8 MW 164 m wind turbine	
U [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 B. 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.
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[1].
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.

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

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