Optimal wind farm power density analysis for future offshore wind farms

ECN cost model evaluation for large wind farms

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ECN

B.H. Bulder
E.T.G. Bot

G. Bedon

Summary

Summary

This report contains the results of a scoping study performed by ECN wind energy for the Ministry of Economic Affairs of the Netherlands.

The Ministry of Economic Affairs has assigned ECN to determine the optimal wind farm power density, in MW/km^2, for future offshore wind farms to be installed.

The wind farms considered will be developed after 2023 and for this study assumed to be located in the currently assigned but yet unused wind farm zones west of the presently developed (near shore) wind farm zones.

In consultation with the ministry we assumed an area of 12 * 30 km, thus 360 km^2, where wind farms were modelled with 10 and 15 MW wind turbines. With each (virtual) wind turbine type 3 different wind farms were modelled and evaluated.

The wind farm designs have a wind farm power density of 4, 7 and 10 MW/km^2. The wind turbines applied in the wind farm designs are based on the following assumptions:

- A rotor power density of 330 W/m^2, resulting in a
    - 10 MW wind turbine with a rotor diameter of 196 m and a
    - 15 MW wind turbine with a rotor diameter of 241 m
- A hub height, above MSL, of 30 + 0.5 rotor diameter.

The wind turbine power curve and axial thrust curve have been determined using ECNs rotor design model BOT.
The wind conditions are assumed to be based on the measurements of the IJmuiden Ver meteorological mast.

The results show that the optimal wind farm power density is 4.66 MW/km^2 for a 10 MW wind turbine and 5.06 MW/km^2 for a 15 MW wind turbine.

A sensitivity study for some of the input / intermediate results show that the result is rather robust and not sensitive to uncertainty of the yield, the capital cost or the cost of O&M and the weighted average cost of capital.

Content

Assignment

Assignment

The assignment is to determine the optimal wind farm power density [MW/km^2], or spacing of wind turbines, for an off shore wind farm and the costs related to deviating from the optimal wind farm power density.

Due to the fact that the answer of this, in itself simple question, is depending on many assumptions, the question is made more specific. The optimal spacing should be determined for a large wind farm where the available space is approximately 350 km^2 and the wind farm will consist of wind turbines that are expected to be commercially available in the period 2024 - 2030. It is anticipated that the location of the wind farms is in the currently assigned but yet unused wind farm zones west of the presently developed (near shore) wind farm zones.

It is agreed to perform the study for:

- 2 different wind turbine types with a nominal power of 10 and 15 MW
- 3 different wind farm power densities, 4 , 7 and 10 MW/ km^2
- ECNs offshore wind energy cost model will be used to determine the energy yield and costs (LCoE)

Next to determination of the optimal wind farm power density it is also investigated what the sensitivity is of several parameters that are set or determined during the project. One which is specifically required to investigate is what will be the influence when a value or cost is applied to the usage of the area, similar to the lease cost of land for an onshore wind farm. Even though there is a large area available off shore there are also many potential usages and when a certain area is assigned to off shore wind energy.

Introduction

Introduction

To assist the ministry of Economic Affairs (EA) of the Netherlands in developing a road map for offshore wind energy after 2023, ECN wind energy has performed a study to determine the optimal wind farm power density .

The optimal wind farm power density is assumed to be that wind farm power density where the Levelised Cost of Energy (LCoE) is minimal.

To perform this analysis it was required to determine a Terms of Reference (ToR) consisting of several design and economic assumptions. These parameters have be determined in cooperation with the ministry of EA.

The ToR consist of information with respect to location, the available area for the wind farm, the wind conditions, the water depth and selection of the nominal power of the wind turbines and the wind farm power densities evaluated. Next to that the fundamental level wind turbine characteristics like rotor power density, i.e. the ratio of the nominal power of the wind turbine over the rotor area, is defined.

Introduction

The analyses performed are:

- Design of 2 simple wind turbines models, using ECNs rotor design code BOT
- Determination of the wind conditions , the wind rose based on 5 years of measurements at IJmuiden Ver Met mast
- Design and performance analysis of 6 wind farms using ECNs wind farm yield analysis tool FarmFlow,
    - 3 wind farms based on a 10 MW wind turbine where the wind farm power density is 4, 7 and 10 MW/km^2 , resulting in wind farms with a nominal power of 1440, 2520 and 3600 MW
    - 3 wind farms based on a 15 MW wind turbine, where the wind farm power density is 4, 7 and 10 MW/km^2 , resulting in wind farms with a nominal power of 1440, 2520 and 3600 MW
- Analysis of the cost, i.e. the capital cost and operational cost, of these 6 wind farms based on ECNs Wind Farm cost model. ECNs wind farm cost model consist s of a semi engineering model predicting the capital cost of the wind turbines, the intra array electrical system, ECN Install, modelling the installation cost, and ECN O&M Access, modelling the O&M strategy and determination of the O&M cost and resulting availability.
- Determination of the optimal wind farm power density and the consequence on Levelised Cost of Energy when a wind farm is constructed with a, different, most likely higher wind farm power density.
- Due to uncertainty of some of the input parameters and results, a limited study has been performed showing the sensitivity of some uncertain input parameters or intermediate results on the resulting optimal wind farm power density.

N.B. The result of the analysis is also depending on the wind turbine characteristics, mainly the rotor power density, however due to limitations in time and budget it is decided to limit this analysis to a single rotor power density (Nominal Power/Rotor area) of 330 W/m^2 .

Introduction

Due to the fact that no detailed cost models are available for these large wind turbines and no experience is available for the technology choices required to make these large wind turbines cost effective the cost model will be based on presently known technologies. Innovations will always lead to cost reductions, otherwise they will not be applied, so the cost values applied here will be conservative.

Cost Model

ECN Wind Energy Cost Model (not identical to policy study model)

Model is based on engineering cost models, making it especially suitable to validate innovations.

ECN integrated Wind Energy cost model consist of sub-models for

- *Energy output*, based on ECNs FarmFlow
- Wind turbine, based on parametric and simple engineering models
- Support structure, based on a simple engineering model
- Electrical infrastructure – inter array (export cable exclude), based on ECNs EeFarm
- Logistics & installation, based on ECNs ECN Install
- Project development - Financial Close, based on simple financial relationship
- Balance of Plant / Other cost, idem.

} Capital cost

- O&M, based on ECNs O&M Access => Operational cost

Cost Model Assumptions and Sensitivities

The simplified cost equation applied, is :

$$LCoE = \frac{\left(\frac{CapEx}{a} + OpEx\right)}{AEP}$$

Where :

LCoE = Levelised Cost of Energy

CAPEX = Capital requirement [€/kW](evaluated with cost model)

OPEX = Annual operational cost [€/year] *(evaluated with the cost model)*

a = Annuity = $^{(1-(1+r)^{-n})}/_{r}$ = 14.2124

r = average discount rate = 3.5%

n = economic lifetime = 20 years

AEP = Annual Energy Production [MWh/year] (*evaluated with cost model*)

Capital Cost Assumptions

		interest /IRR
Equity	25%	8%
Debt	75%	2%
Discount rate (WACC)		3.5%

Terms of Reference

ToR – Location parameters

Location: Hollandse Kust 3, West of the HK Zuid and Noord.

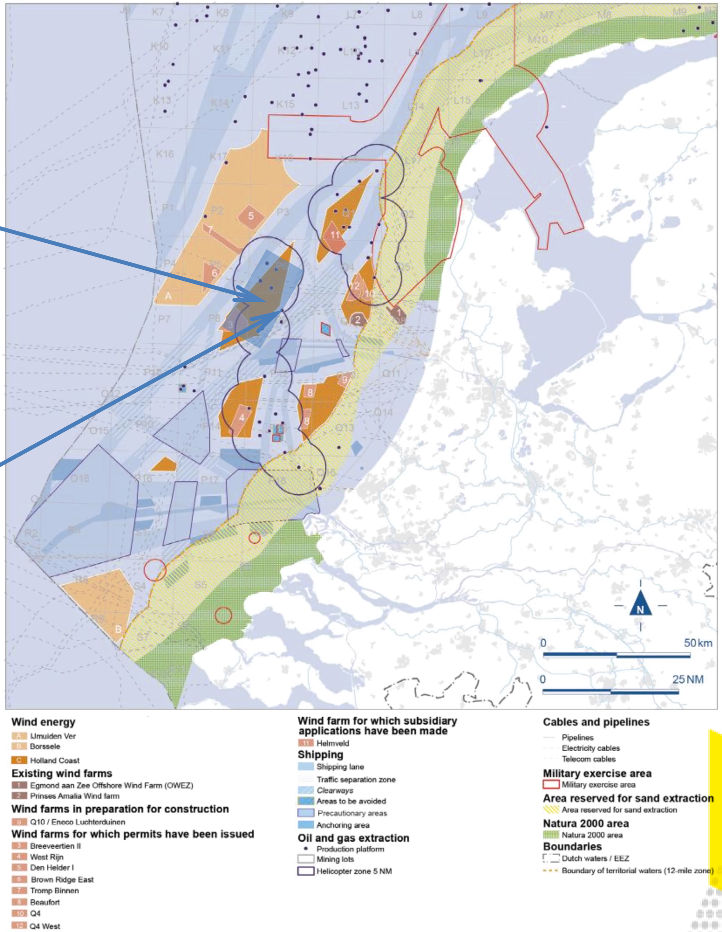
Assumption are:

- Distance to shore 80 [km]
- Met Ocean conditions equal to IJmuiden Ver
- Area used to model the wind farm a square of 12 by 30 km, totalling to 360 km^2 oriented with the long direction 30^0 rotated from North to East

- The intra array electrical system is 66 kV and per 820 MW a substation is applied. The cost of the substation and export cable to shore are not taken into account

Ministerie van Infrastructuur en Milieu

Appendix 1 Map of the Holland Coast area



ToR - Wind Resources (based on Met Mast IJmuiden ver)

The wind rose at the hub height of a 10 MW wind turbine

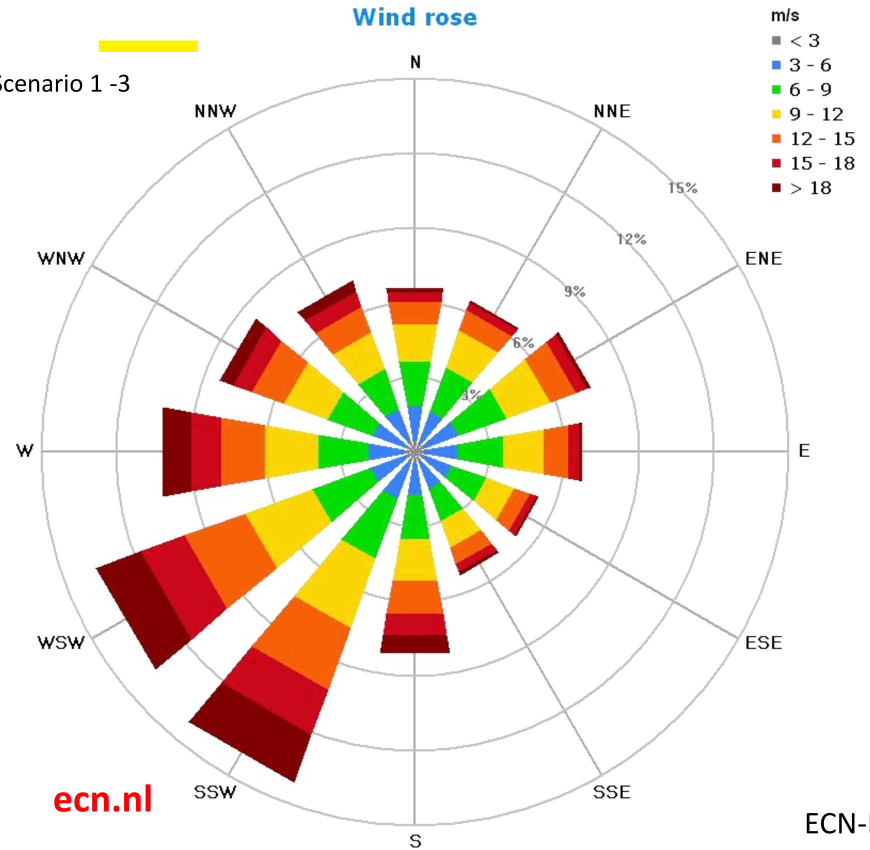
Scenario 1 - 3					
Reference height:	128.2	[m]			
Air density at reference height:		1.230	kg/m³		
Weibull data for 12 wind sectors					
Sector	Frequency [%]	Weibull A [m/s]	Weibull k [-]	Wind [m/s]	Power density [kWh/m²/year]
N	6.653	9.972	2.255	8.834	425.07
NNE	6.471	9.793	2.375	8.681	376.31
ENE	7.520	10.213	2.374	9.053	495.94
E	6.848	10.191	2.320	9.03	456.51
ESE	5.294	9.611	2.200	8.513	309.28
SSE	5.280	9.859	2.080	8.735	350.35
S	8.242	11.866	2.063	10.513	959.58
SSW	14.130	13.508	2.306	11.968	2198.7
WSW	13.620	13.500	2.340	11.963	2091.9
W	10.260	12.596	2.174	11.156	1360
WNW	8.357	11.461	2.169	10.151	836.77
NNW	7.326	10.993	2.053	9.74	681.88
All	100.0	11.573	2.200	10.254	1090.2

The wind rose at the hub height of a 15 MW wind turbine

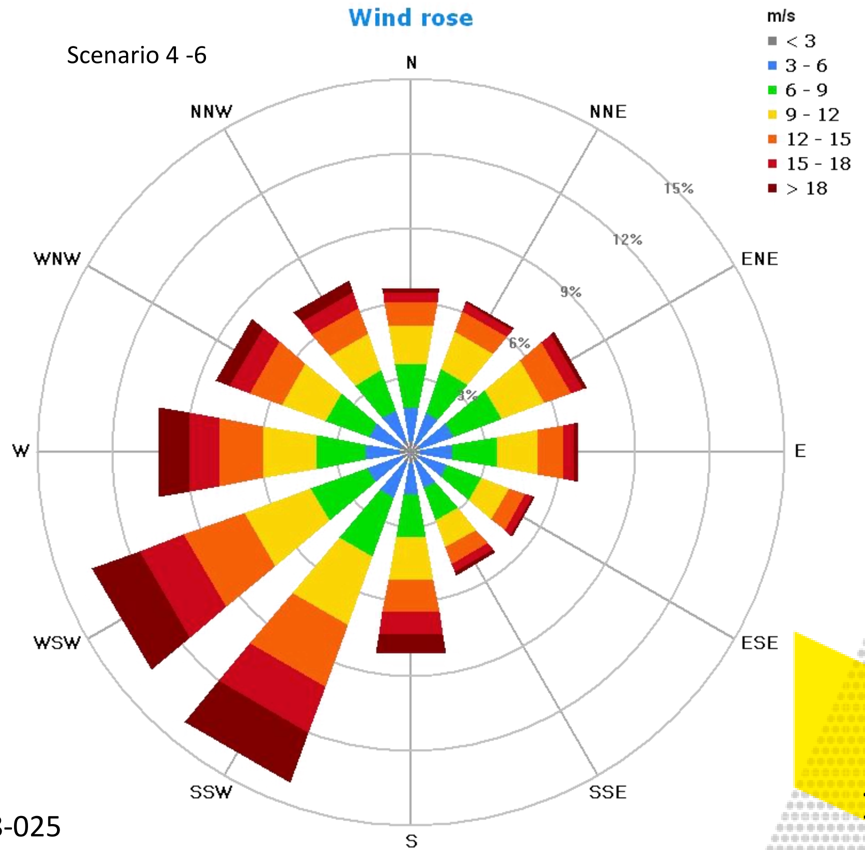
Scenario 4 - 6					
Reference height:	150.3	[m]			
Air density at reference height:		1.227	kg/m³		
Sector	Frequency [%]	Weibull A [m/s]	Weibull k [-]	Wind [m/s]	Power density [kWh/m²/year]
N	6.653	10.090	2.256	8.938	439.05
NNE	6.471	9.909	2.375	8.783	388.84
ENE	7.520	10.333	2.374	9.159	512.31
E	6.848	10.311	2.320	9.137	471.61
ESE	5.294	9.725	2.200	8.614	319.59
SSE	5.280	9.976	2.080	8.838	362.04
S	8.242	12.006	2.063	10.637	991.44
SSW	14.130	13.668	2.306	12.11	2272
WSW	13.620	13.660	2.340	12.105	2161.8
W	10.260	12.745	2.174	11.288	1405.3
WNW	8.357	11.596	2.169	10.271	864.49
NNW	7.326	11.123	2.053	9.855	704.56
All	100.0	11.710	2.2	10.375	1126.5

ToR - Wind Resources (based on Met Mast IJmuiden Ver)

Scenario 1 -3



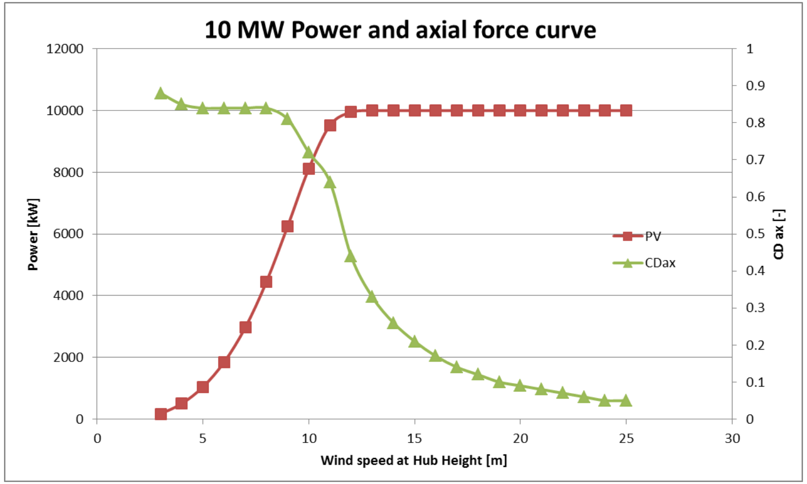
Scenario 4 -6

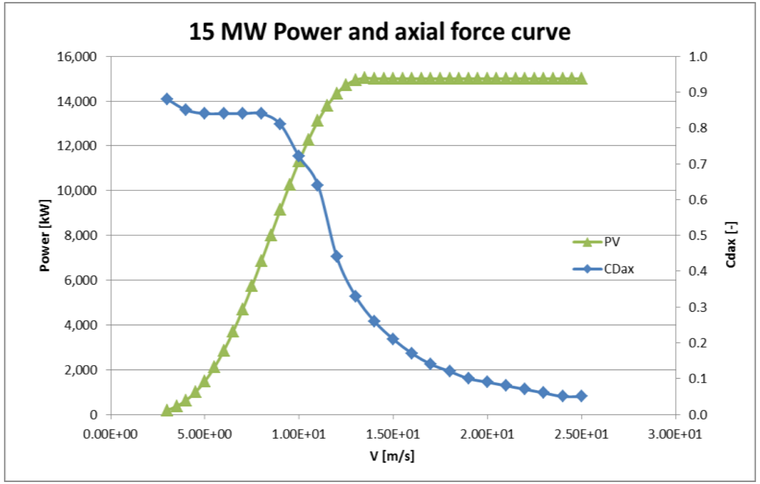


ToR - Wind Turbines, characteristics

- Wind turbine rotors with a rotor power density of 330 W/m2, resulting a
  - 10 MW with a rotor diameter of 196.4 m and a
  - 15 MW with a rotor diameter of 240.6 m.
- Other design considerations and parameters applied based on experience of ECN Wind Energy

Resulting in a power curve and axial force coefficient curve required to analyse the performance of the wind farm, shown below.





Evaluations

Evaluations

The following 6 scenarios are evaluated; 2 different wind turbines applied in 3 wind farms with a different Wind Farm Power Density (WF PD). For ease of comparison the resulting spacing between wind turbines is also calculated.

For each scenario a wind farm has been designed where the average wind farm power density is applied. The spacing however is optimised in such way that the yield is optimised by varying the spacing ;where the spacing is increased in the main wind direction, see slide 18, and decreased in the direction perpendicular to the main wind direction.

Scenario	WT Power [MW]	WT Diameter [m]	WF Power [MW]	WF Power Density [MW/km^2]	Number of WT [-]	Spacing [D]
1	10	196.4	1440	4	144	8.0
2	10	196.4	2520	7	252	6.1
3	10	196.4	3600	10	360	5.1
4	15	240.6	1440	4	96	8.0
5	15	240.6	2520	7	168	6.1
6	15	240.6	3600	10	240	5.1

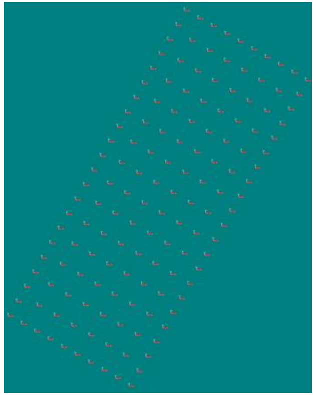
Relation between wind turbine spacing S [D] and WF PD [MW/km^2] is not linear, where RPD is the Rotor Power Density [W/m^2]:

$$S[D] = \sqrt{\left(\frac{1}{4}\frac{\pi}{\mathrm{WF}}\frac{\mathrm{RPD}}{\mathrm{PD}}\right)}$$

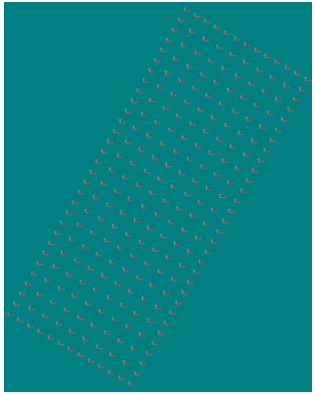
Evaluations

6 wind farms have been designed and evaluated to determine the yield, total investment costs and operational costs.

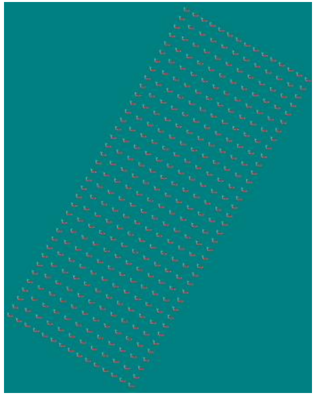
Scenario 1 (144 WT's)



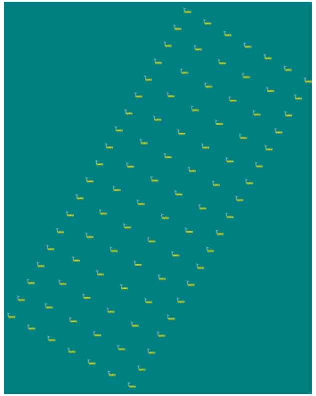
Scenario 2 (252 WT's)



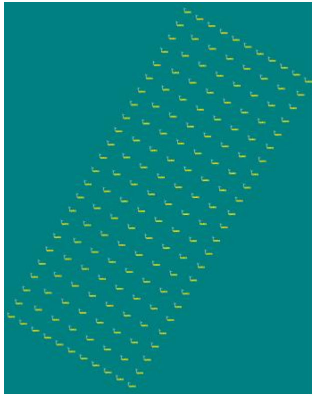
Scenario 3 (360 WT's)



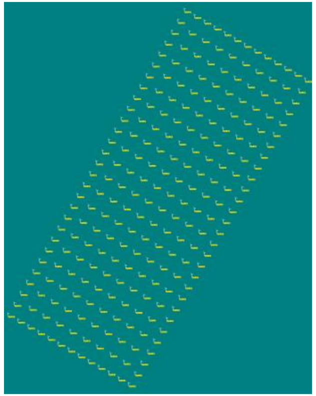
Scenario 4 (96 WT's)



Scenario 5 (168 WT's)



Scenario 6 (240 WT's)



Results ECN cost model

Cost modelling

The 6 scenarios are modelled in ECNs cost model. The resulting cost divided in

- Capital cost based on the cost of
  - the wind turbines,
  - the cost of the foundations,
  - the cost of the electrical infrastructure and
  - the cost of the installation
- Operational cost based on cost of
  - O&M
  - Other cost
  - Availability of the wind farm
- The Annual Energy Production
  - the gross energy yield after wake losses is determined with FarmFlow.
  - the gross yield is reduced for availability and
  - the electrical losses inside the wind farm.

The results are evaluated in the cost analysis, shown in slide 12 and 13.

The resulting Levelised Cost of Energy for the 6 scenarios are fitted against the wind farm power density (WFpd in [MW/km^2]) or the inter turbine spacing in rotor diameters [D].

The fit is performed with a linear or quadratic curve which ever gives the best fit.

N.B. the overall cost might seem high compared to presently reported cost results, however ECNs cost model is developed for wind turbines with a nominal power between 5 – 8 MW and could not be adjusted / tuned with presently achieved values.
The output is seen best as a relative comparison towards the optimum.

Results of ECNs cost model – Overall Cost

Scenarios		1	2	3	4	5	6
Wind Turbine Power	[MW]	10	10	10	15	15	15
Wind Farm Power	[MW]	1440	2520	3600	1440	2520	3600
Number of WT	[-]	144	252	360	96	168	240
WF Power density	[MW/km^2]	4	7	10	4	7	10
Average spacing	[D]	8.0496	6.0849	5.0910	8.0496	6.0849	5.0910
Total							
CAPEX	*[M€]*	3001	5232	7458	3271	5713	8150
CAPEX	*[M€/MW]*	2.084	2.076	2.072	2.271	2.267	2.264
OPEX	*[M€/year]*	228	373	510	180	305	438
OPEX	*M€/MW/year]*	0.158	0.148	0.142	0.125	0.121	0.122

Results of ECNs cost model – Wind Farm Performance, yield, losses and availability

Scenarios		1	2	3	4	5	6
WakeFarm Results	[MWh/y]	7,275,201	12,139,324	16,546,521	7,439,435	12,503,544	17,181,849
Wake Farm Efficiency	[%]	93.2	88.8	84.8	94.4	90.6	87.2
E-losses WT Transformers	MWh/year]	23,042	38,454	52,422	23,556	39,592	54,409
Relative losses due to WT Transformer	[%]	0.32%	0.32%	0.32%	0.32%	0.32%	0.32%
Net Energy yield at turbine tower foot	[MWh/y]	7,252,159	12,100,870	16,494,099	7,415,879	12,463,952	17,127,440
Net energy yield at substation 100% availability	[MWh/y]	7,159,113	11,947,483	16,284,298	7,321,703	12,306,606	16,913,390
Electrical efficiency inside the array	[%]	98.40%	98.42%	98.42%	98.42%	98.42%	98.44%
Net Energy yield	[MWh/y]	6,772,521	11,266,476	15,274,672	6,662,750	11,518,983	15,966,240
Net Capacity factor	[%]	53.7%	51.0%	48.4%	52.8%	52.1%	50.6%

Results of ECNs cost model – Turbine

Turbine							
Scenarios		1	2	3	4	5	6
Total	*[M€]*	*11.631*	*11.631*	*11.631*	*19.553*	*19.553*	*19.553*
Total	*[M€/MW]*	*1.163*	*1.163*	*1.163*	*1.304*	*1.304*	*1.304*
Turbine Electric	[M€]	0.615	0.615	0.615	0.837	0.837	0.837
Turbine Gearbox	[M€]	1.588	1.588	1.588	2.904	2.904	2.904
Turbine Generator	[M€]	0.212	0.212	0.212	0.269	0.269	0.269
Turbine Hub	[M€]	0.790	0.790	0.790	1.366	1.366	1.366
Turbine Main shaft	[M€]	0.549	0.549	0.549	0.950	0.950	0.950
Turbine Nacelle	[M€]	1.094	1.094	1.094	1.893	1.893	1.893
Turbine Miscellaneous	[M€]	0.514	0.514	0.514	0.711	0.711	0.711
Turbine Rotor	[M€]	2.672	2.672	2.672	4.619	4.619	4.619
Monopile Tower	[M€]	3.319	3.319	3.319	5.667	5.667	5.667
Electricity WT Transformers	[M€]	0.278	0.277	0.278	0.336	0.336	0.336

Results of ECNs cost model – Electrical cables - Installation – O&M

Electrical Infrastructure							
Scenarios		1	2	3	4	5	6
Total	*[M€]*	85.600	137.150	189.200	66.800	114.900	153.800
Total	*[M€/MW]*	0.059444	0.054425	0.052556	0.046389	0.045595	0.042722
Array String cable	*[M€]*	85.6	137.15	189.2	66.8	114.9	153.8
Installation							
Scenarios		1	2	3	4	5	6
Total	*[M€]*	*304.677*	*526.544*	*742.964*	*240.930*	*412.890*	*589.340*
Total	*[M€/MW]*	*0.212*	*0.209*	*0.206*	*0.167*	*0.164*	*0.164*
O&M							
Scenarios		1	2	3	4	5	6
O&M availability (yield)		0.946	0.943	0.938	0.91	0.936	0.944
Total - O&M - Revenu Losses	*[M€/year]*	*227.604*	*372.562*	*510.404*	*179.564*	*304.958*	*437.623*
Total O&M cost / MW	*M€/MW/year]*	*0.158*	*0.148*	*0.142*	*0.125*	*0.121*	*0.122*

Process to determine optimal wind farm power density

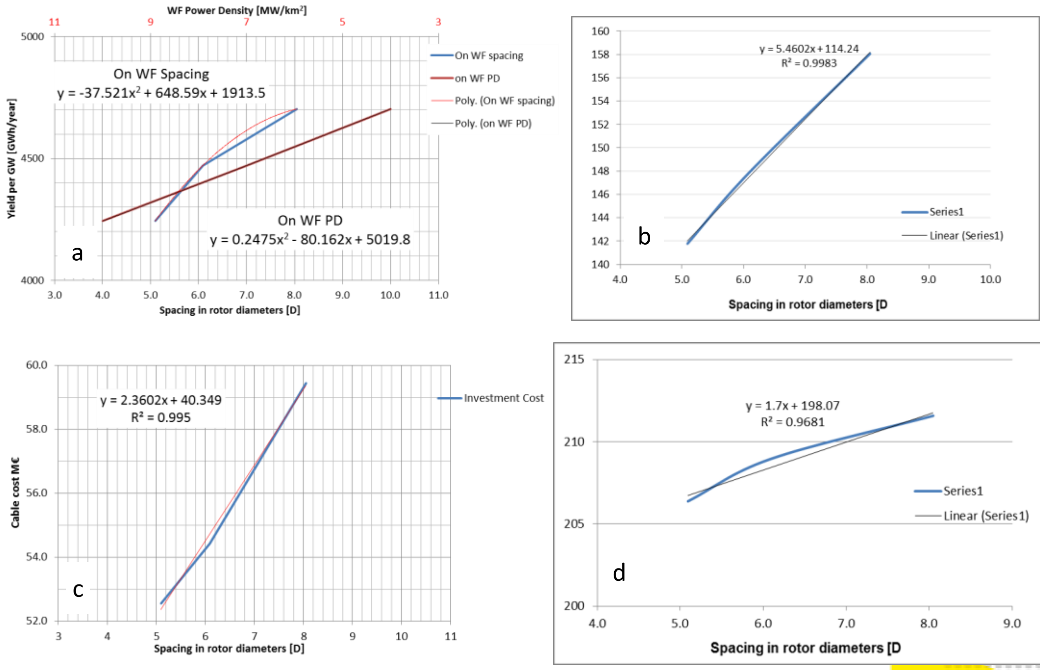
The process applied to determine the optimal spacing is based on determination of the yield, O&M cost, Installation cost and cable cost as a function of the spacing in rotor diameters [D] or in wind farm Power Density.

a) The net wind farm yield, after wake losses and electrical losses, shown in figure on the top, is fitted with a linear function against the wind farm power density or a quadratic function against the wind farm spacing.

b) The O&M cost per MW/ year plotted linearly against the spacing, see on the right

c) The cable cost is fitted linearly against the wind farm spacing

d) The installation cost is fitted linearly against the wind farm spacing

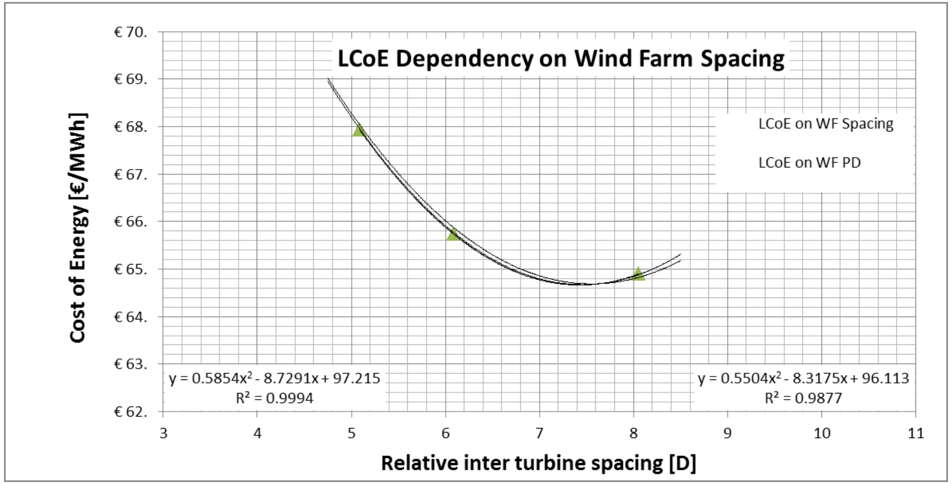


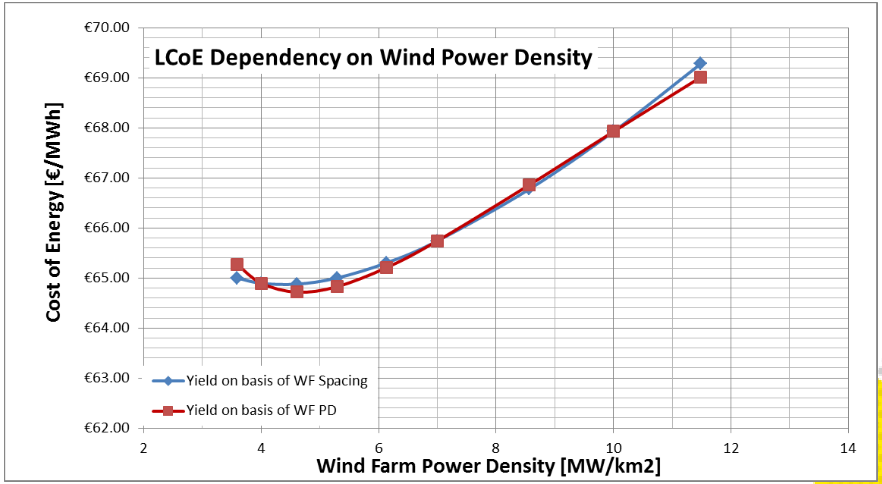
Results 10 MW Case

Applying the relations on yield and costs in the cost of energy analysis are plotted against the inter turbine spacing and the wind farm power density.

The points in between the actual determined values, i.e. for a wind farm power density of 4, 7 and 10 MW/km^2 are based on evaluations of the curves determined on the previous slide.

Optimal spacing is 7.46 [D] which is equal to 4.66 [MW/km^2]

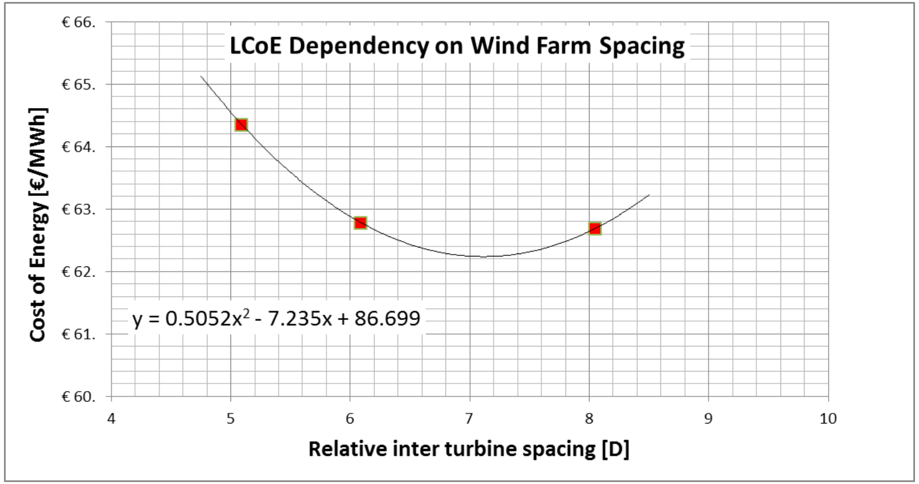


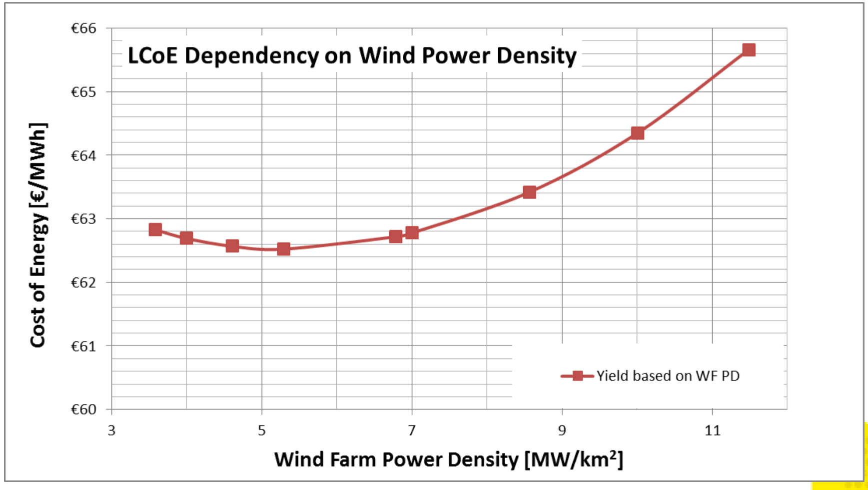


Results 15 MW Case

The results for the 15 MW wind turbine case are:

Optimal spacing is 7.16 [D] which is equal to 5.06 [MW/km^2]





Variations – robustness of the result

Variations – robustness of the results

To investigate the sensitivity or robustness of the result a simple parameter variation has been applied in determination of the optimal spacing or wind farm power density.

By varying the following parameters in the cost analysis by + or – 10%

- Capital cost;
- O&M cost;
- Discount rate;
- Yield,

the resulting optimal wind farm power density is determined.

The results show that the sensitivity is not high, for the 10 MW scenario the optimal wind farm power density varies between 4.61 and 4.72 [MW/km^2], while for the 15 MW scenario the sensitivity is even lower.

10 MW scenario

Factor		Optimal spacing [MW/km^2]		
		+10%	0%	-10%
Capital cost	[-]	4.61	4.66	4.72
O&M	[-]	4.72	4.66	4.61
Discount rate	[-]	4.69	4.66	4.62
Yield	[-]	4.61	4.66	4.72

15 MW scenario

Factor		Optimal spacing [MW/km^2]		
		+10%	0%	-10%
Capital cost	[-]	5.06	5.06	5.07
O&M	[-]	5.07	5.06	5.04
Discount rat	[-]	5.06	5.06	5.06
Yield	[-]	5.04	5.06	5.07

Variations – robustness of the result

To investigate sensitivity of the cost of sea space the cost of “land lease” is added to the operational cost of the wind farm.

The sensitivity of the optimal wind farm power density is quite strong; when adding small lease prices per km^2 to the annual Opex cost the optimal wind farm power density will reduce as shown below:

10 MW scenario

Annual Lease Cost [M€/km^2]	Spacing [D]	WF PD [MW/km^2]
0.000	7.46	4.66
0.050	7.00	5.29
0.100	6.60	5.95
0.150	6.24	6.66

15 MW scenario

Annual Lease Cost [M€/km^2]	Spacing [D]	WF PD [MW/km^2]
0.000	7.16	5.06
0.050	6.63	5.90
0.100	6.18	6.79
0.150	5.81	7.68

Discussion – Conclusion - Recommendations

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In the this study the optimal wind farm power densities are determined for two different wind turbine types, one with a nominal power of 10 and one with a nominal power of 15 MW. To determine the optimal wind farm power densities, the costs and performance are determined for 3 different wind farm power densities [MW/km^2] for both wind turbine types. Next to the optimal wind farm power densities also the sensitivity of the result has been determined by varying several parameters +/- 10%.

The optimal wind farm power density for a 10 MW wind turbine is 4.6 [MW/km^2] and for a 15 MW wind turbine the optimal wind farm power density is 5.06 [MW/km^2]. The results show that the optimal wind farm power density is slightly higher, approximately 4%, for a 15 MW compared to a 10 MW wind turbine. The main reason for this increase is that the optimum spacing of wind turbines is determined by balancing the increase in cost of electrical cables and losses in these cables with the lower aerodynamic losses due to wake effects. For a 15 MW wind turbine the number of wakes and thus the wake effects are lower due to a lower number of wind turbines for the same nominal power wind farm which allows that larger wind turbines can have a slightly higher wind farm power density, than the smaller wind turbine.

The sensitivity of the investigated input and intermediate result parameters is not substantial with one exception. The sensitivity for the cost or lease of the usage of sea area is substantial. By applying a cost of k€ 50 per km^2 the optimal wind farm power density is increased by approximately 15%.

One input parameter is not varied and might have a substantial influence on the result and that is the assumed rotor power density or the rotor diameter for each wind turbine. It is recommended to determine the influence of that parameter on the resulting optimal wind farm power density.