Upwind E-system upscaling and reliability

EeFarm II calculations

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Abstract: Trends in upscaling and reliability for electrical system of offshore wind farms based on 5 and 20 MW turbines, wind farm sizes of 500 and 1000 MW and distances to shore of 25, 100, 200 and 500 km have been investigated. The EeFarm-II program for wind farm electrical and economic evaluation has been used for this investigation.

The EeFarm-II model calculates the output voltage and current phasor (AC) or voltage and current value (DC) of each wind farm component based on the input voltage and current and the component parameters. This is repeated for the complete operation range of the wind farm, i.e. the range of input wind speed. Secondly, the total investment of the electrical system (if wind turbine prices are not included) or of the wind farm (if wind turbine prices are included) is determined. Based on the output power for each wind speed bin and the wind speed distribution, the annual produced energy is determined. The final step is the calculation of the Levelised Production Costs (LPC).

For the collection system in the wind farm 32kV and 69kV AC are taken into account, for the connection to shore the options are 150kV AC, 245kV AC, ±80kV DC and ±150kV DC. For the 500 MW wind farm with 5 MW turbines the 32kV option is marginally better. For the 500MW wind farm at 25 km 150kV AC gives the lowest LPC. For 100, 200 and 500km, ±150kV DC is the best solution.

Keywords: offshore wind farm electrical systems, offshore wind farm design, offshore wind farm economics.

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Contents

1 Introduction

The aim of work package Electrical Grid of the Upwind project is to investigate the requirements to wind turbine and wind farm design due to the need for reliable wind power in electric power systems and to study possible solutions that can improve wind power reliability. The task is particularly important for large offshore wind farms, since the failure of a large wind farm can have a significant impact on the power balance in the power system. Wind farm (component) reliability is also important because offshore wind farms are normally more difficult to access than land-sited wind farms.

The work package Electrical Grid of the Upwind project will investigate operational as well as statistical aspects of wind farm reliability. Investigating grid code requirements, extreme wind conditions and specific wind farm control options to cope with these requirements will cover the operational aspects. The statistical aspects will be covered by the development of a database and by modelling of the effect of component reliability and redundancy on the power production and the energy price of wind farms.

The work package Electrical Grid of the Upwind project also investigates trends in electrical design criteria and grid connection costs due to upscaling, i.e. increasing the wind turbine size to 20 MW and the offshore wind farm size to 500-1000 MW.

In this report reliability, redundancy and upscaling are investigated by calculating voltages, currents, losses, not produced power due to component failure, nett produced power, investment costs, nett produced energy and Levelised Production Costs for 500 MW and 1000 MW wind farms with different electrical systems. Electrical systems based on AC as well as DC connections to shore will be investigated. DC connection in the wind farm itself, i.e. between the turbine and the wind farm platform, will not be taken into account. The reason is the lack of recent budget prices for some of the components required for these systems. Earlier studies, which included systems with DC connections inside the wind farm, which were (partly) based on dated budget prices, showed that these are not cost effective yet.

For wind farm modelling the EeFarm-II program is used. EeFarm-II is a steady-state model, comparable to a load flow model but with the possibility to include DC components. EeFarm-II calculates the output voltage and current phasor (AC) or voltage and current value (DC) of each electrical component in a wind farm, based on the input voltage and current and the component parameters. The voltages and currents are calculated for a given wind speed, i.e. a given input power. This is repeated for each wind speed bin over the complete operation range of the wind farm. Based on the wind farm output power for each wind speed and the wind speed distribution, the annual produced energy is determined. Secondly, the total investment cost of the electrical system (if wind turbine prices are not included) or of the wind farm (if wind turbine prices are included) is determined. The final step is the calculation of the Levelised Production Costs (LPC).

Component failure will have a significant effect on the wind farm annual energy production (AEP) and the levelised production cost (LPC). This is caused by the on average relatively long repair times for offshore facilities, due to rough weather conditions at sea. Therefore, component failure and redundancy are included in the estimation of the AEP and LPC. A non-availability module has been included in EeFarm-II as part of this project, which takes redundancy into account.

This report evaluates different electrical system options for large wind farms with large wind turbines for different wind turbine sizes and distances to shore. The evaluation makes use an up-to-date database with component parameters and investment costs (see appendix A to C). The objective is to determine trends for the electrical system in the transition from medium size offshore wind farms to large wind farms with large wind turbines.

This report consists of three main parts. Chapter 2 introduces the EeFarm-II program and describes the new features added to determine the effect of component failure and redundancy on the produced energy and the Levelized Production Costs (LPC). Chapter 3 specifies the wind farm main design parameters. In chapter 4 the electrical system options (Cases) for the 500 MW wind farm with 5 MW turbines will be determined and the results (investment costs, power and energy production, losses, not produced energy due to component failure and LPC) will be presented. In chapter 5 gives the results for the 1000 MW wind farm with 20 MW turbines. Finally, chapter 6 discusses the trends and draws conclusions.

2 EeFarm II introduction and new features

2.1 Introduction

EeFarm II is a computer program and database for the analysis of wind farm electrical systems.

The Software

EeFarm-II has been developed to study and optimise the steady state 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 turbines, generators, transformers, AC and DC cables, PWM (pulse width modulated) and thyristor converters and of an inductor, statcom and chopper.

EeFarm-II 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 [1], can be fed into the turbine blocks.

The Model

EeFarm-II 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. EeFarm-II 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.

The Database

EeFarm-II calculations require component parameters (typically resistances, capacitances and inductances) and budget prices which are stored in a component database. Ideally the parameters and budget prices should be supplied by component manufacturers and should be updated regularly. A database with manufacturer supplied component parameters is included; budget prices however are not included due to confidentiality agreements.

The Experience

EeFarm-II was originally developed by ECN and Delft University of Technology in MATLAB. To improve user-friendliness, it was completely rebuilt in MATLAB-Simulink, exploiting the advantages of the Simulink graphical user interface and MATLAB data structures. This second version was developed and tested in collaboration with Vattenfall Sweden. Vattenfall was also the first customer of EeFarm-II. The models comprising the program have been partly validated (only AC components) by comparison to the Vision load flow program.

EeFarm-II has been developed with financial support from the We@Sea reseach program.

The EeFarm II program can be used to investigate the effect of wind farm component choice (costs, losses, reactive power consumption), layout (turbine locations and interconnection) and component control on the voltages, currents, total electrical losses, not produced energy due to not-availability and production costs. Examples of aspects of an investigation are:

- different cable routing and location of transformer platforms;
- different component types and ratings, especially the effect of different cable choices;

- reactive power control by variable speed wind turbine generators;
- AC versus DC connections;
- redundancy, especially the effect of multiple cables to shore.

For a description of the EeFarm II program is referred to [8].

2.2 Availability and redundancy in EeFarm II

Load flow programs such as Vision [4] can calculate the overall electrical system reliability from the system layout and the reliability of the individual components [5]. Since component failure can have a significant effect on the production of offshore wind farms, due to the low accessability of the wind farm and the time it takes to repair components such as offshore cables, the effect of component reliability and repair times should be included in wind farm electrical and economic evaluations. EeFarm II takes the effect of component failure on the power production of the wind farm into account, but in a different way then Vision. In Vision, the effect of failure of an individual components and redirection of the power flow is evaluated, including possible overloading of the grid. This redirection of power flows is essential in medium voltage meshed grids, the main application of Vision. The medium voltage grid is designed with this redirection in mind. In the case of offshore wind farms however, there is no meshed grid. Generally there is only one route for the power from any turbine location in the farm to the HV grid connection point at shore. In rare cases, more than one route is possible, for instance if the total farm power is devided over two high voltage cables to shore. Only in these rare cases a limited amount of redundancy (at below rated power) exists. Due to the simplicity of offshore wind farm grids, the effect of component failure on the total production can be determined in a relatively simple way: by applying a component non-availability factor to the power produced by or passing through each component. This method is implemented in EeFarm-II, under the following considerations:

- The non-availability factor is calculated from the MTBF (Mean Time Between Failure, failure rate) and the MTTR (Mean Time To Repair). The MTTR has to include the effect of the weather on the possibility to repair offshore wind farm components.
- EeFarm-II determines the power produced by or passing through a component at a given location in the farm for a given wind speed bin. The average power lost due to failure is determined by multiplying the power minus the power lost due to failure of upstream components by the non-availability factor of the component.
- EeFarm-II component output power, voltage, current and reactive power are not corrected for the power loss due to non-availability. The component is either failed (off state) or in operation (on-state). The output power, voltage, current and reactive power are values in the on-state (no components failed).
- EeFarm-II corrects the ohmic losses for component non-availability.
- EeFarm-II assumes that only one component fails at a time (no multiple failure). Then there are no upsteam components of a failed component which failed at the same time, which would reduce the total power lost by failure of the downstream component.
- Wind farm maintenance can be included in the non-avalability if it is assumed that the maintenance is random, i.e. it is not executed during low wind periods. In that case the maintenance frequency and the maintenance duration have to be known.

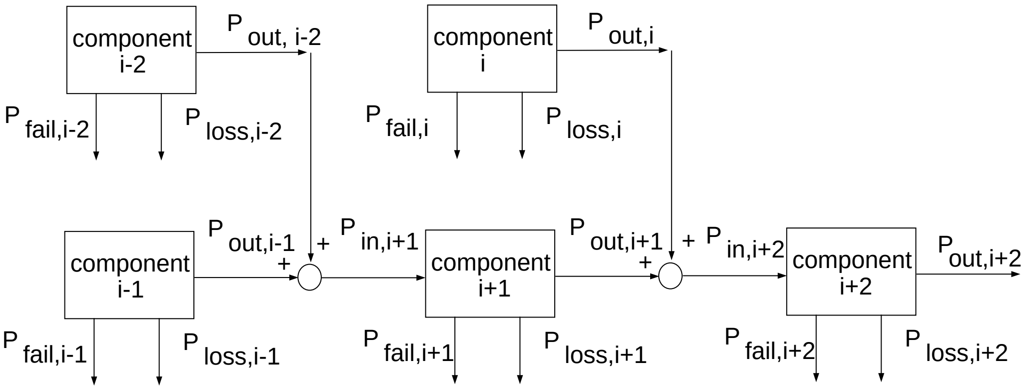

Figure 1: *Component string availability calculation*

Figure 1 shows the availability calculation. The ohmic losses $P_{loss,i}$ and the energy not produced due to failure $P_{fail,i}$ are added for all components and are determined by:

$$\begin{aligned}
P_{out,i} &= P_{in,i} - P_{ohmic,i} \\
P_{fail,i} &= f_{na,i}(P_{out,i} - \Sigma P_{fail,i}) \\
P_{loss,i} &= (1 - f_{na,i})P_{ohmic,i}
\end{aligned}$$

with:

$P_{in,i}$: input power of component i (without failure)
$P_{out,i}$: output power of component i (without failure)
$\Sigma P_{fail,i}$: sum of average power reduction of components upsteam of component i due to failure of components upsteam of component i
$f_{na,i}$: the non-availability factor of component i: i.e. the fraction of time that component i is not in operation due to failure (and possibly also maintenance)
$P_{fail,i}$: average output power reduction of component i due to failure of component i
$P_{ohmic,i}$: ohmic and switching losses in component i (not corrected for the failure of component i)
$P_{loss,i}$: average ohmic and switching losses in component i, i.e. corrected for the failure of component i
$\Sigma P_{loss,i}$: total ohmic losses of component i and components upsteam of component i (corrected for the failure of component i and components upsteam of component i)

The calculation can be represented by a Sankey diagram, with three flows for each component: the generated power, the power lost due to internal resistance and the power not produced due to failure and repair.

Figure 2: *EeFarm II generic and cable availability block*

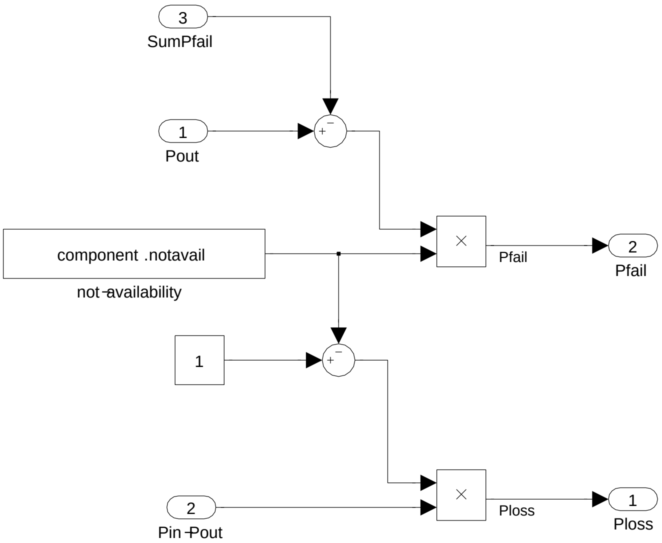

Figure 3: *EeFarm II generic availability block*

2.3 Redundancy

As part of the Upwind project, redundancy has been added to the non-availability calculation of EeFarm-II. Redundancy aspect to be considered are:

- parallel components, for example parallel WF transformers and parallel cables to shore;
- overdimensioning in combination with parallel components;
- redundant parallel components, only included to stand in for a failed component, i.e. a special case of overdimensioning;
- redundant series components, creating an alternative current path, for example creating a ring structure in the wind farm by adding a cable btween the two ends of a string.

To include redundancy in the EeFarm-II calculation, the availability model has been extended with a redundant apparant power level S_{redun}. Below the redundant apparant power level, failure of the component is fully compensated by parallel components and power redirection. Above the redundant apparant power level, only the redundant apparant power can be transported.

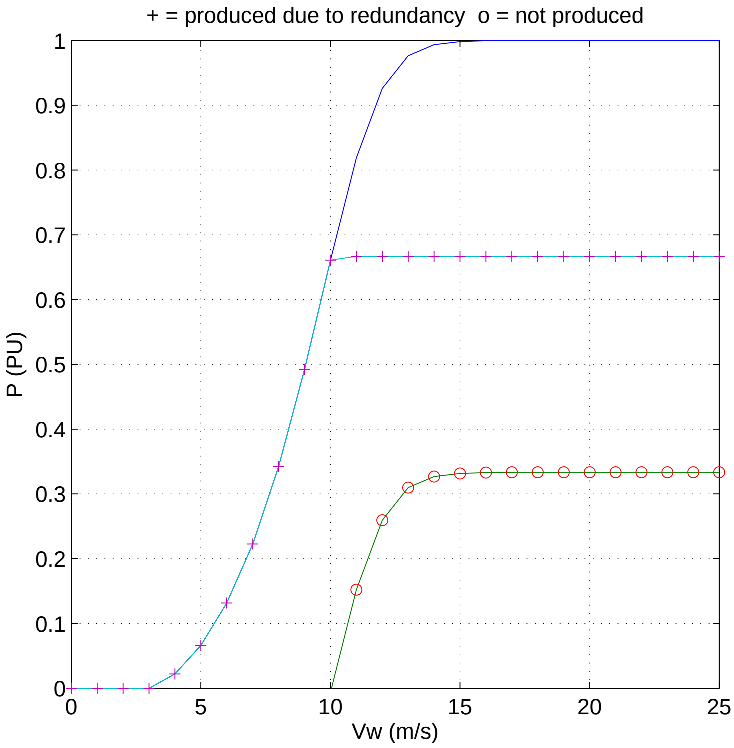

Figure 4: *Production during a failure of one of three parallel components*

Failure of a parallel component only reduces the power production if the apparent power surpasses the total redundant apparent power of the components remaining in operation (assuming that the failed component can be isolated from the system). For example, if the total farm power is transformed by 3 parallel transformers of 33.3% of the rated WF apparent power each, energy production is only reduced if the total wind farm apparent power exceeds 66.6%. Since the EeFarm-II calculation is executed per wind speed bin, failure of one component does not reduce the apparent power below 66.6% and caps the production at 66.6%, see figure 4. Multiple failure, i.e. failure of 2 parallel component at the same time, is not considered in EeFarm-II.

With redundant apparant power level S_{redun}, not produced power due non-availability only occurs if $S > S_{redun}$:

$$\begin{array}{rcl} \text{if } S_{out,i} \leq S_{redun} & & \\ P_{fail,i} & = & 0 \\ P_{loss,i} & = & P_{ohmic,i} \\ \text{if } S_{out,i} > S_{redun} & & \\ P_{redun,i} & = & \sqrt{S_{redun}^2 - Q_{out,i}^2} \\ P_{fail,i} & = & f_{na,i}(P_{out,i} - P_{redun,i} - \Sigma P_{fail,i}) \\ P_{loss,i} & = & (1 - f_{na,i})P_{ohmic,i} \end{array}$$

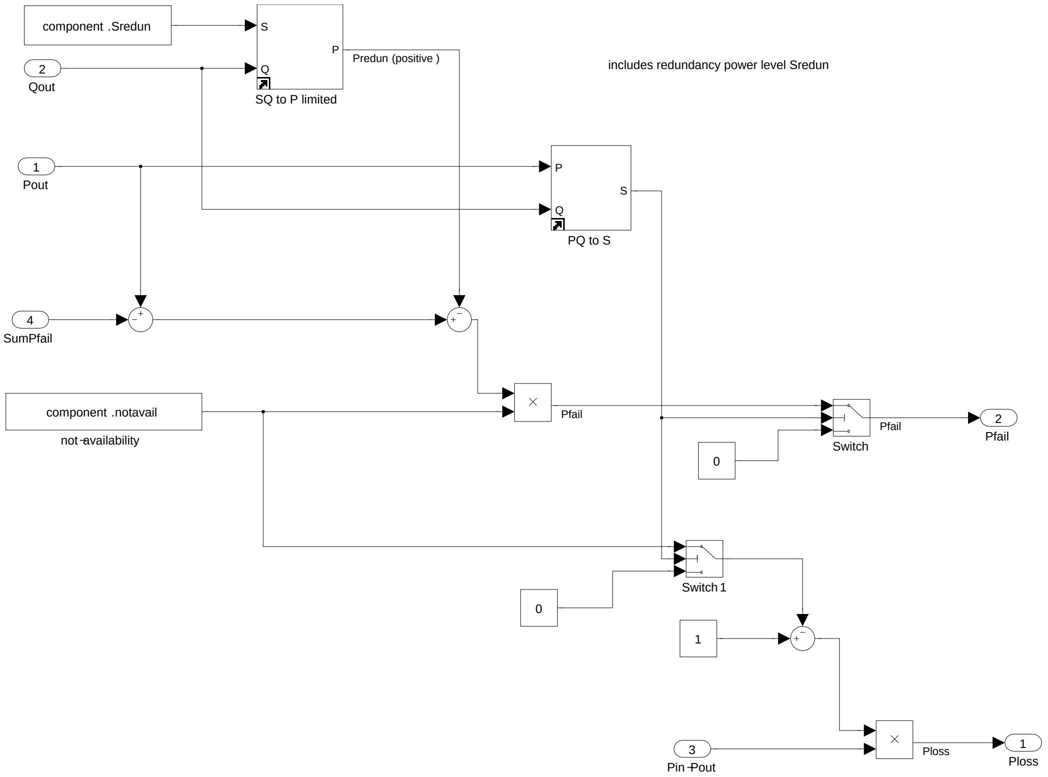

Figure 5: *EeFarm II availability block including redundancy*

Figure 5 shows the modified availability block. The value of S_{redun} is component and location specific and is calculated in the initialization section, when the component parameters are set. For N parallel components, $S_{redun} = \frac{N-1}{N} S_{rated}$.

2.4 Cable failure in a ring structure

Failure of a component in a ring structure is a bit more complicated. Now the maximum power to be transported depends on the location of the component that failed. If a component at the start or the end of the ring failed the maximum apparent power to be transported by the intact part of the ring is higher than in case a component fails in the middle of the ring. The maximum power level passing through a connection is fixed however. The ratio between the component rated power and the maximum power of the ring is used to correct the power not produced due to non-availablity. No actual redirection of the power is calculated. Instead, only the fraction of the power that can not be transported is determined.

For a daisy chain connection of turbines of equal rating, connected in a ring, the fraction of the total apparent power that can be transported depends on the location of the failure and the rating of the cable. For instance if the first cable fails, which is the worst case, only half the maximum total turbine apparent power can be transported, if the cables are rated at $N_{tur}P_{tur}/2$, which is a logical choice. If the middle cable fails, which is the least bad, all apparent power can be transported, since the ring can also be operated as two strings without interconnection at the end. The average fraction of the maximum apparent power that can be transported by a ring structure during a failure of a single cable will therefore lie between 0.5 and 1.

Since it is a lot of work to give each individual cable section in a wind farm a different redundancy level S_{redun}, EeFarm-II calculates an average redundant apparent power for all cables in a ring and all individual cable failures. This average value is used for all cable sections in the ring. The average redundant apparent power depends on the cable rating and the number of cable sections but not on the individual cable location. It is assumed that the cables in the ring all have the same rated power. Figure 6 gives the average redundant apparent power

S_{redun} in per unit for a string of variable length, 2 to 30 turbines and for three cable ratings: $S_{cab} = N_{tur} * S_{tur}/2$ (A), $S_{cab} = N_{tur} * S_{tur}/2 + S_{tur}$ (B) and $S_{cab} = N_{tur} * S_{tur}/2 + 2S_{tur}$ (C). For a large number of turbines the average redundancy level converges to about 0.75. For a practical number of turbines in the ring, i.e. 5 to 15, the values are in the range of 0.70-0.74, 0.86-0.80 and 0.96-0.85.

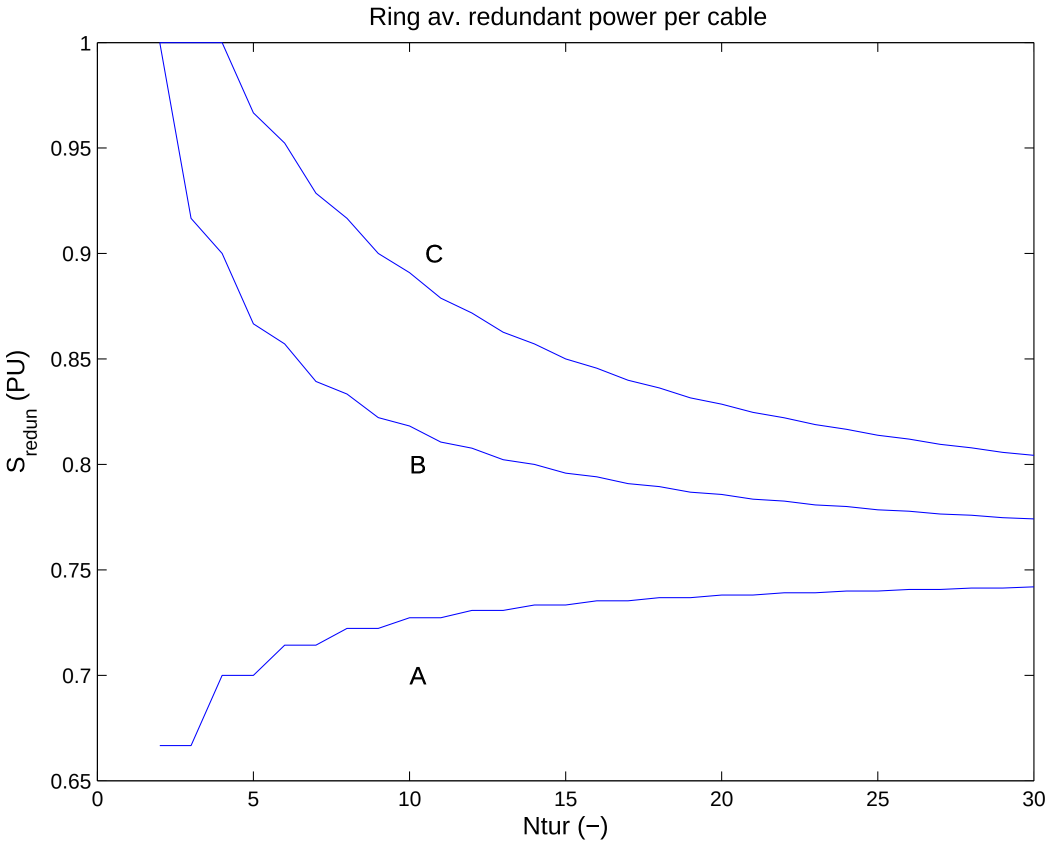

Figure 6: *Average redundancy level for a daisy chain ring structure and single cable failure for 3 cable ratings*

The calculation of the average redundant apparent power S_{redun} for a ring connection is included in EeFarm-II as a subroutine. Input parameters are the number of turbines, the turbine rated power and the cable rated power. The number of cable sections is equal to the number of turbines plus one.

Calculating the non-availability per wind speed bin (with equal power for each wind turbine) has the advantage of being fast. But there is also a disadvantage, compared to a Monte Carlo calculation with different power levels per wind turbine. The Monte Carlo calculation is a better representation of the actual situation. If, however, a Gausian distribution with an equal chance of a higher as well as a lower wind speed is assumed, the Monte Carlo calculation will not deviate much from the calculation with equal power for each wind turbine. The disadvantage of a Monte Carlo calculation is the much longer time it takes to be completed.

2.5 Tapchanger

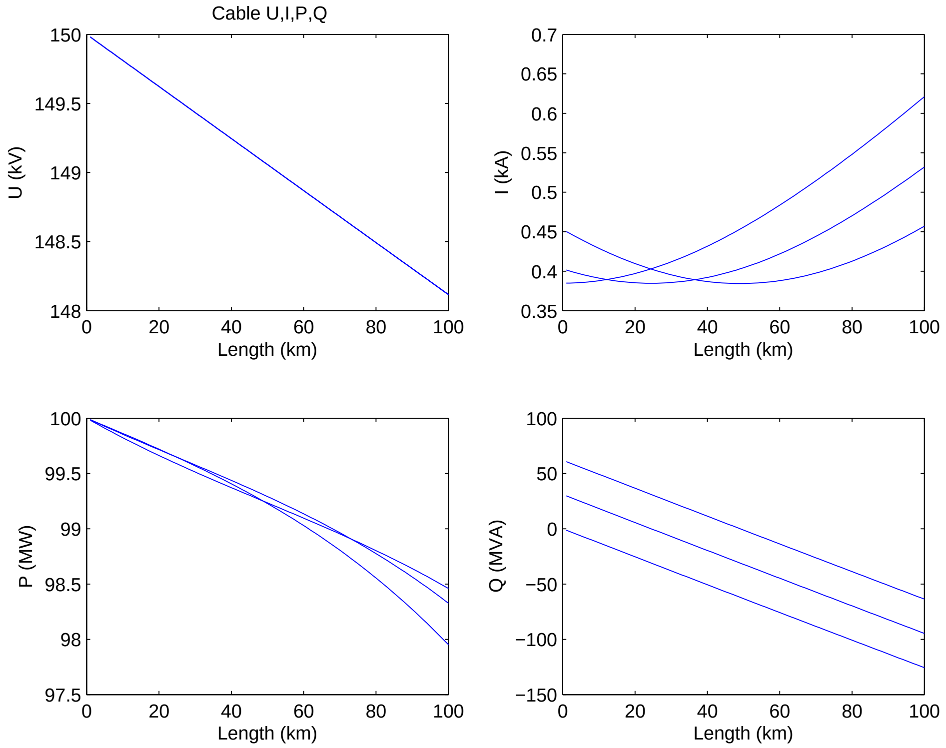

Figure 7: *Voltage, current, power and reactive power in a 100 km 150 kV cable for three values of input reactive power*

The second new item added to EeFarm-II in the Upwind projects is an automatic tap changer model. EeFarm-II uses a voltage drop calculation without iteration. The voltage and current phasor calculation starts with the rated voltage at the wind turbine and stops at the grid connection point. Since the voltage decreases in the direction of the power flow, the voltage at the grid connection point will be a few percent below the shore cable rated voltage. The voltage level inside the farm can be regulated by tap changers in the transformers. The effect of a slightly different voltage level in the farm on the losses will be small for three reasons:

- for a long AC cable to shore, the voltage at the wind farm side will be the nominal value of the cable and the voltage at the grid side will be a few percent lower, see figure 7. The reduced voltage at the grid side of the cable will not be compensated by the grid transformer to prevent overvoltage at the wind farm side of the cable.
- a higher voltage in the farm cables decreases the active current but increases the reactive current in the cables. Both effects more or less balance and there is practically no effect on the current amplitude and the losses;
- even if the reactive current would not increase, the effect of a few percent increase of the active current is small since the active and reactive current in the cable to shore are often of about the same size. Then the active current increase does not increase the current amplitude much;

For a more accurate voltage level calculation the model of an automatic tap changer has been added to EeFarm-II, see figure 8. Based on the transformer rated output voltage, the required voltage ratio is calculated from the input voltage and the assumption of 20 tap positions in plus and minus direction and a maximum compensation of 10%.

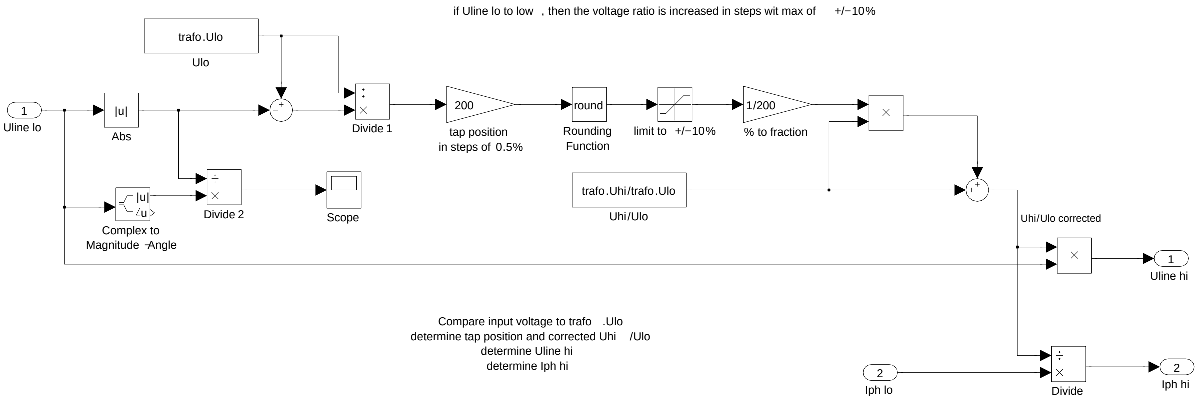

Figure 8: *EeFarm II tap changer block*

2.6 Subbusses

The third item added to EeFarm-II in the Upwind project is the new subbus structure. It is useful to know the investment costs, the losses and the not produced power due to component failure per component type. This gives an idea how to improve the wind farm performance and serves as a check, since the relative contributions of the different component types are similar in most wind farms and by comparing different cases errors can often be located. The component type values of the investment costs, the losses and the not produced power due to component failure are determined in EeFarm-II by introducing subbusses for these signals in the bussignal that connects the component blocks. Each subbus consists of 18 signals: 17 for the different component types and one for the sum over all types. At input data level, each component type is specified by a vector consisting of 16 zeros and 2 ones. Figure 9 shows the subbus update block.

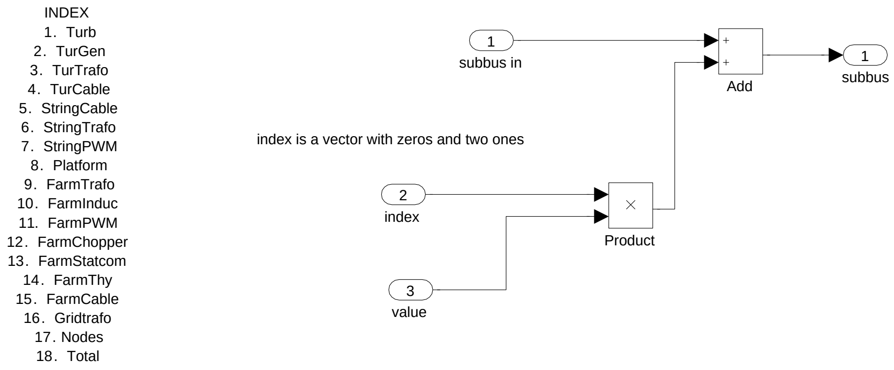

Figure 9: *Subbus update block*

3 Offshore Wind Farm Design Parameters

The overall parameters are based on the reference wind farms defined in the Upwind project. The turbine specifications are:

Wind turbine electrical power (MW)	5	10	15	20
Wind turbine type	VS	VS	VS	VS
Rotor diameter D (m)	126	178	218	252
Tip speed (m/s)	80	80	80	80
Hub height H (m)	90	116	136	153

Only the 5 and 20 MW wind turbines are selected for the EeFarm-II Upscaling and Reliability calculations. The wind farm specifications are:

Reference wind farm (MW)	500	1000
Water depth (m)	30	60
Turbine distance (D)	7	7
Turbine location	square grid	square grid
Distance to shore (km)	25, 100, 200	100, 200, 500
Area	Square	Square

The main electrical system specifications are:

Wind farm cables (kV)	33, 66
Shore cables (kV)	150 kVAC, 220 kVAC, 150 kVDC, 300 kVDC
Nr. of platforms	one platform per 250 MW (275 MVA)
Reactive power compensation	WF and grid side

For the EeFarm-II Upscaling and Reliability calculations a single platform with farm and system specific size is selected. The economic parameters are:

Interest rate (nominal)	7%
Inflation	2%
Economic lifetime (y)	20
Weibul parameter v_{av}	9.7 m/s
Weibul parameter s	2.08

The reliability parameters are [7]:

	Failure rate (y^{-1})	Average repair time (days)	Non-availability factor (-)
String cable	0.007/km	20	0.007*20/365 /km
String to platform cable	0.007/km	20	0.007*20/365 /km
Transformer at platform	0.043	40	0.043*40/365
VSC converter	0.2	20	0.2*20/365
Shore cable AC	0.011/km	20	0.011*20/365 /km
Shore cable DC	0.011/km	20	0.011*20/365 /km
Inductor	0.001	40	0.001*20/365
Node, connector	0.0001	10	0.0001*10/365

Turbine failure and repair is not included in the reliability calculation. The repair times are based on a dedicated maintenance plan for a large wind farm of 0.5-1 GW (full time maintenance personel and permanently available equipment for all types of repair).

In case of a single bipolar DC connection, the redundant apparent power level is $0.5S_{rated}$, assuming that the bipolar connection can temporarily be operated in monopolar mode. All DC connections in this report are bipolar.

It is assumed that, in case of parallel components, redirection of the power from the failed component to the parallel component is possible.

4 Wind farm cases @ 5MW, 0.5GW

4.1 Components and layouts

Since the main specifications in section 3 still offer different options, a set of cases is defined based on the main specifications. The cases are named as follows. The case number corresponds to the configuration, determined by the components and the cable layout inside the farm. A different distance to shore is indicated by the letters A, B, C or D corresponding to 25, 100, 200 and 500 km respectively, see table 1.

Table 1: Case matrix 500 MW

Case nr.	1A	2A	5A	2B	4B	5B	7B	5C	7C	8C
Cable 33kV	X									
Cable 69kV		X	X	X	X	X	X	X	X	X
Dist 25 km	X	X	X							
Dist 100 km				X	X	X	X			
Dist 200 km								X	X	X
AC, 150 kV	X	X		X						X
AC, 245 kV					X					
DC, 150kV			X			X		X		
DC, 300kV							X		X	

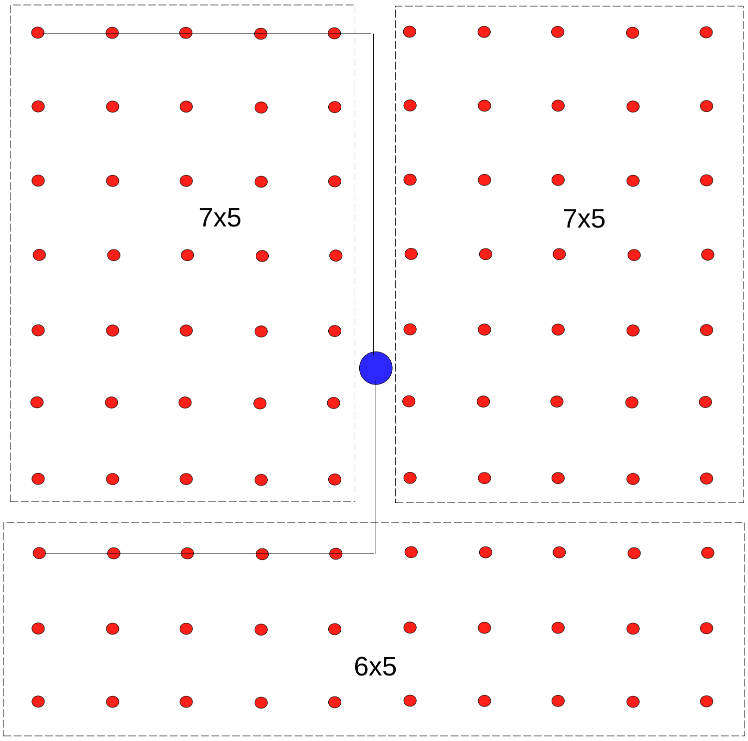

Figure 10: *Case 1 (33kV-27MVA) internal connection scheme (150kV, 3x to shore)*

For large wind farms multiple cables to shore have to be used. A division of the turbine power over the shore cables has to be made. This can be implemented by sectioning the farm (each section feeds a different shore cable) or by feeding the total power to a single point and using a splitter. Sectioning the wind farm may lead to a slightly different layout, since the section maximum power has to correspond with the cable power. In the EeFarm-II calculations the wind farms will be sectioned.

Case 1 component choice:

- five turbines per string, so 5x5=25 MW, rating: 33 kV, 27.5 MVA;
- turbine/string cable options: cable nr. 9, 30kV-28MVA or nr. 12, 32kV-27MVA or nr. 24, 32kV-27MVA. Choice: nr. 12;
- nr. of platforms: 1, location of the platform at the farm center;
- connection scheme: see figure 10;
- the number of high voltage AC cables in the database is limited:
  - cable nr.15: 138 kV - 149 MVA;
  - cable nr.14: 150 kV - 200 MVA;
  - cable nr.27: 150 kV - 190 MVA;
  - cable nr.18: 245 kV - 346 MVA;
  - cable nr.19: 245 kV - 367 MVA;
- for Case 1 the options for the cable(s) to shore are: 4x nr.15 (600MVA), 3x nr.14 (600MVA), 3x nr.27 (570MVA), 2x nr.18 (692MVA), 2x nr.19 (734MVA);
- choice cable to shore Case 1: 3x cable nr.27 (150kV-570MVA).

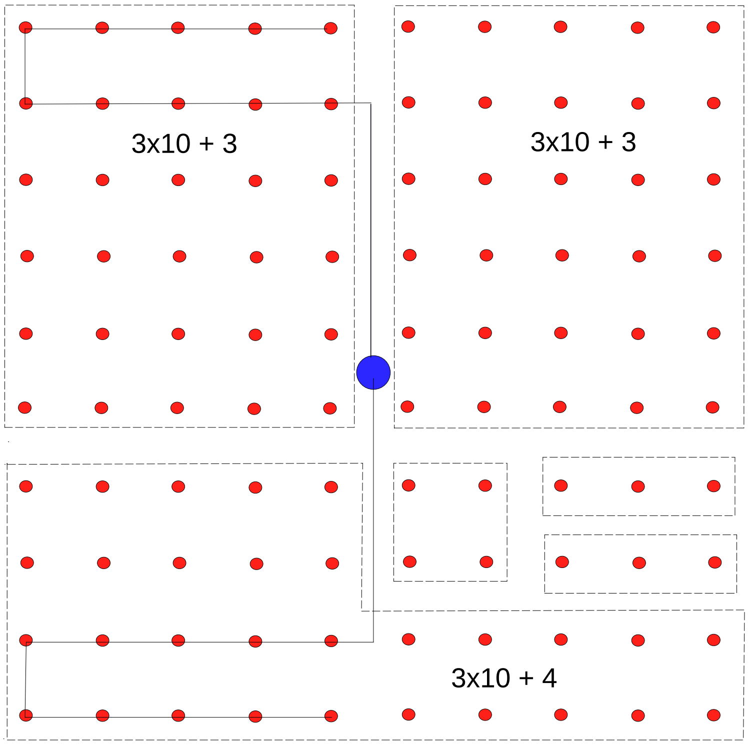

Figure 11: *Case 2 (69kV-58 MVA) internal connection scheme (150kV, 3x to shore)*

Case 2 component choice:

- compared to Case 1, the voltage of the cables connecting the turbines to the substation is increased to 69 kV;

- ten turbines per string, so 10x5=50 MW, rating: 69 kV, 55 MVA;
- turbine/string cable choice: cable nr.26, 69 kV, 58 MVA;
- nr. of platforms: 1, location of the platform at the farm center;
- connection scheme: see figure 11;
- choice cable to shore Case 2: 3x cable nr.27 (150kV-570MVA).

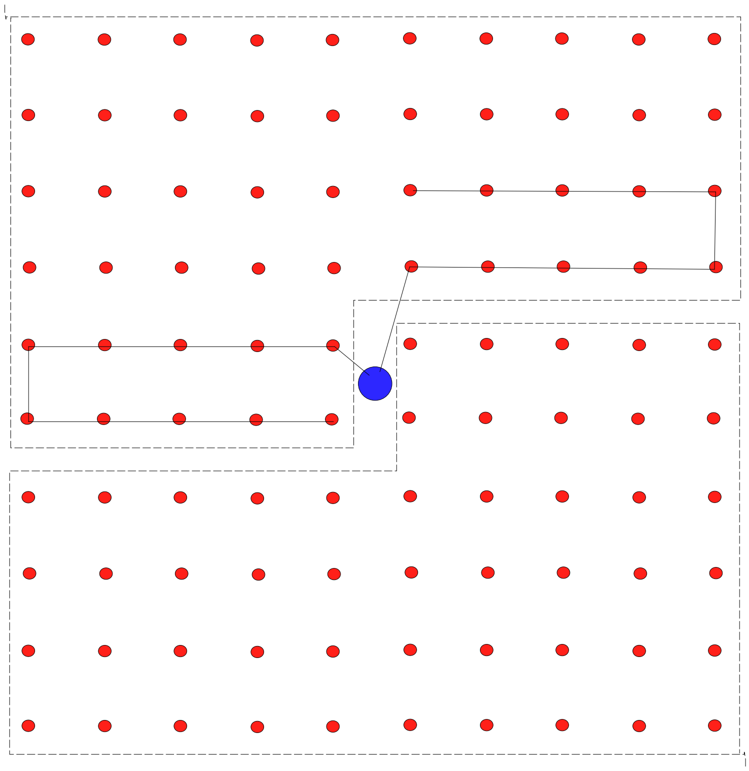

Figure 12: *Case 4 (69kV-58 MVA) internal connection scheme (245kV, 2x to shore)*

Case 4 component choice:

- compared to the previous cases 1 and 2, the voltage of the cable to shore is increased to 245kV in Case 4;
- ten turbines, so 10x5=50 MW per string, rating: 69 kV, 55 MVA;
- turbine/string cable choice: cable nr.26, 69 kV, 58 MVA;
- cable to shore choice (100 km): 2x nr.18 (245kV-692MVA)
- nr. of platforms: 1, location of the platform at the farm center;
- connection scheme: see figure 12;

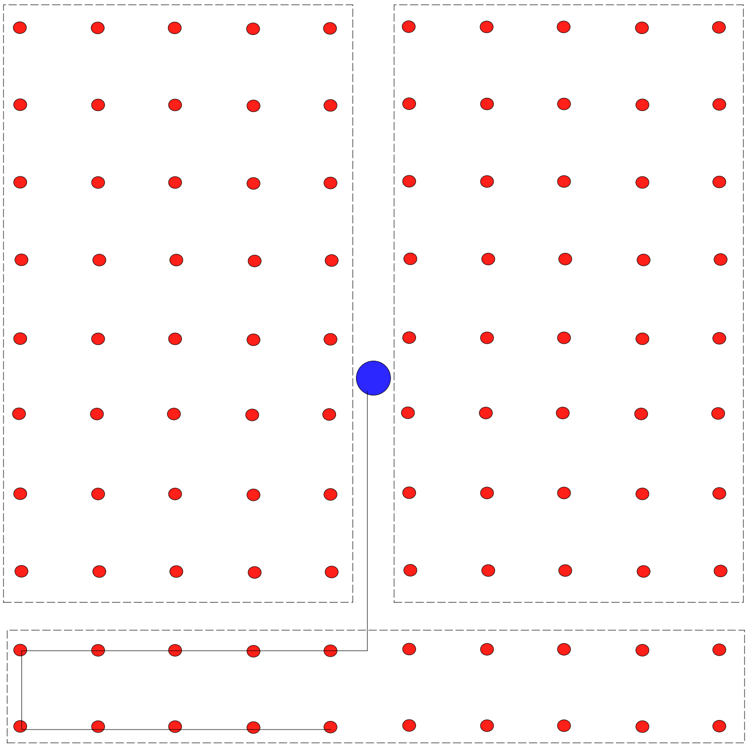

Figure 13: *Case 5 (69kV-58 MVA) internal connection scheme (+-80kV DC, 2x200MW + 1x100MW to shore)*

Remark on the DC cable choice:

Options for the rating of the DC cable are:

- to choose the same rating as the rectifier and the inverter (the most obvious solution);
- to choose multiple cables for a single set of rectifier/inverter;
- to connect multiple rectifiers and inverters to a single cable of higher rating (multiterminal connection, not common technology yet).

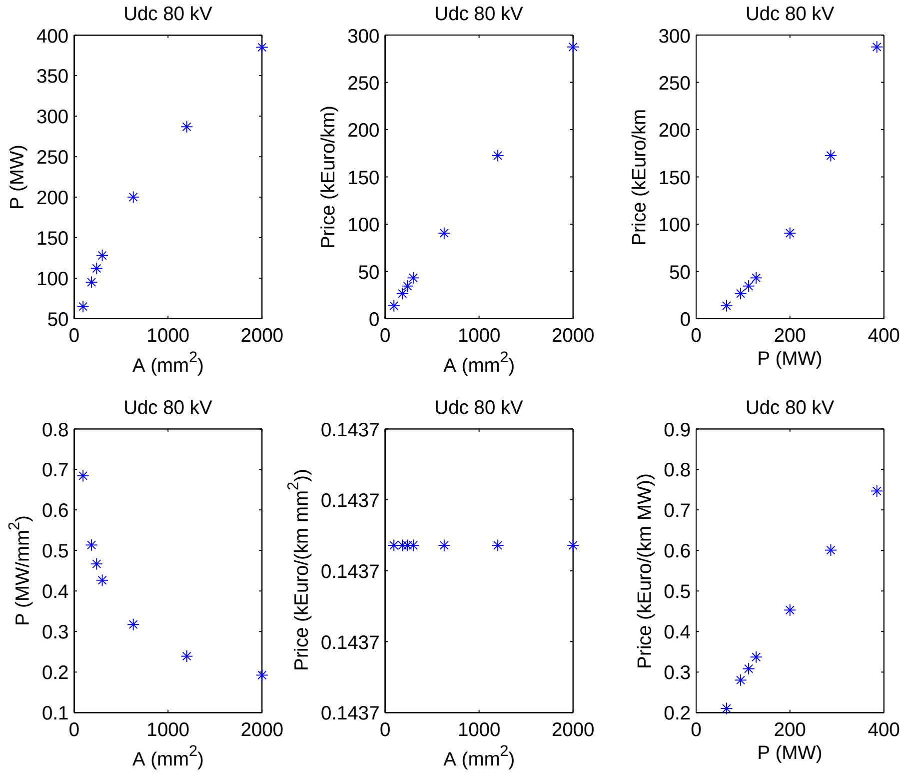

Figure 14: *DC cable prices as function of crosssection and power (80kV)*

A single DC cable for the total rated wind farm power is expected to be cheaper to manufacture and reduces laying costs, but also reduces redundancy. The cable manufacturer supplied data for three voltage-area values: ±80kV-1000mm^2, ±150kV-1000mm^2 and ±320kV-2000mm^2. The cables with different areas have been calculated from these values assuming a linear dependance on the area. Now figure 14 shows that at constant voltage:

- the rated power increases less than linearly with the crossectional area;
- the price increases more than linearly with the rated power.

For higher cable ratings, a reduction in cost can still result from reduced installation costs. DC cable losses are a function of the cable area only (if temperature is assumed constant) and the different manufacturers use the same values, see figure 28.

The DC cable in the EeFarm-II upscaling and reliability calculations will have the same or slightly larger rating as the PWM converter, so a single (bipolar) cable per set of recifier/converter.

Case 5 component choice:

- Case 5 is the first case with a DC connection to shore;
- available ±80kV PWM converters in database: nr.1 (101 MW) and nr.2 (199 MW);
- PWM converter choice for 500 MW: 2x nr.2 and 1x nr.1;
- DC cable to shore: 2x nr. 5 (80kV and 200MW) and 1x nr. 3 (80kV, 112 MW);
- nr. of platforms: 1, location of the platform at the farm center;
- same turbine and string cable as in Case 2;
- connection scheme: see figure 13;

Case 7 component choice:

- compared to Case 5, the DC voltage of the cable to shore is increased to ±160kV;
- available ±160kV PWM converters in database: 190, 373 and 570MW;
- PWM converter choice: nr. 5 (570MW);
- DC cable to shore: nr. 13: 150kV, 537MW;
- nr. of platforms: 1, location of the platform at the farm center;
- same turbine and string cable as in Case 2;
- same connection scheme as Case 4: see figure 12;
- a single 500MVA transformer.

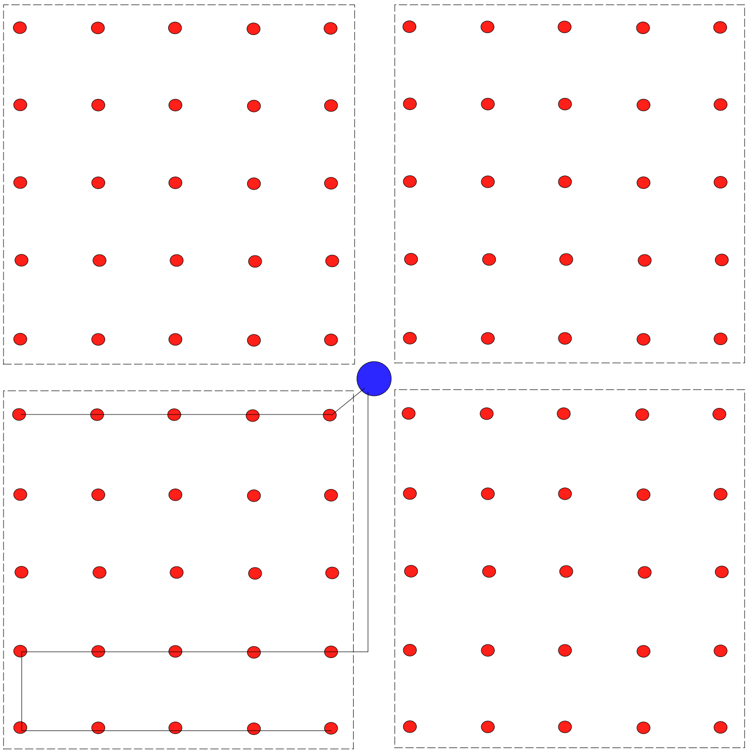

Figure 15: *Case 8 (69kV-58 MVA) internal connection scheme (150kV, 200km, 4x to shore)*

Case 8 component choice:

- this case again uses a AC connection to shore;
- the distance to shore is 200km, the number of AC cables has to increase due to the increase in capacitive cable current, see figure 16. Since the reactive power of the 245kV cables (nr. 18 and 19) is significantly higher than of the suitable 150kV cable (nr. 27), three 245kV cables or four 150kV cables are required for 500 MW. Since the price of the 245kV cable is twice as high as the 150kV cable, the 150kV option is chosen;
- for a sufficiently accurate calculation of the reactive power over the length of the cable to shore, the number of cable sections is increased to 10;
- nr. of platforms: 1, location of the platform at the farm center;

- same turbine and string cable as in Case 2;
- connection scheme in the farm: see figure 15;
- four 150MVA transformers.

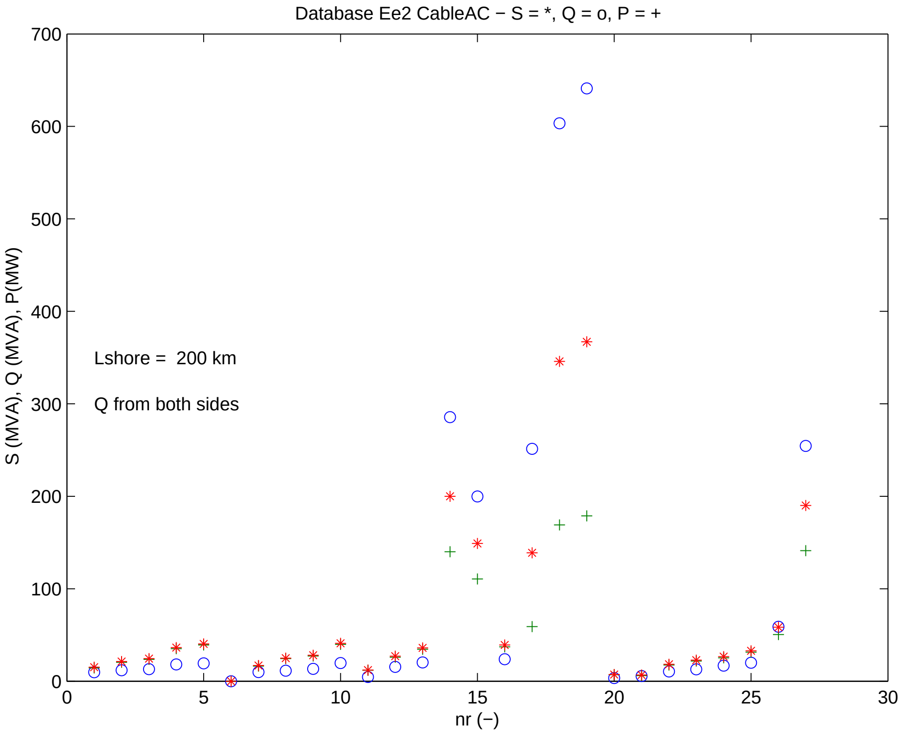

Figure 16: *AC cables - Q and maximum P for 200 km (P assumes equal Q compensation at both cable ends)*

Table 2: Component matrix 500 MW cases

	Case 1				Case 2				Case 4				Case 5			
	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.
Turbine	-	0.96	5	100	idem				idem				idem			
Tur trafo	T	32	6.25	100	idem				idem				idem			
Tur cable	12	32	27	100	26	69	58	100	idem				idem			
String cable	12	32	27	10	26	69	58	10	idem				idem			
Farm trafo	T	150	190	3	T	150	190	3	T	245	300	2	T	107	200	2
Farm trafo													T	107	100	1
Inductor	I	150	5	3	idem				I	245	100	2				
Farm AC cable	27	150	190	3	idem				18	245	345	2				
PWM conv													1	80	100	1
PWM conv													2	80	200	2
Farm DC cable													3	80	112	1
Farm DC cable													5	80	200	2

	Case 7				Case 8											
	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.
Turbine	-	0.96	5	100	idem											
Tur trafo	T	32	6.25	100	idem											
Tur cable	26	69	58	100	idem											
String cable	26	69	58	10	26	69	58	12								
Farm trafo	T	197	500	1	T	150	150	4								
Inductor					I	150	125	4								
Farm cable	13	150	537	1	27	150	190	4								
PWM conv	5	150	570	1												
Farm DC cable	13	150	537	1												

DB: component number in database, T: transformer p.u. parameters, I: inductor p.u. parameters

4.2 Results 500 MW

Table 3: *Investment and power (at max wind speed)*

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
Case1A	108.6	487	13.3	3.1	2.7	0.6	484
Case1A-NR	108.6	487	13.3	10.5	2.7	2.1	476
Case2A	113.7	490	10.4	3.4	2.1	0.7	486
Case2A-NR	113.7	490	10.4	10.9	2.1	2.2	479
Case5A	212.9	466	33.9	7.1	6.8	1.4	459
Case2B	244.5	480	19.9	8.9	4.0	1.8	471
Case4B	250.0	480	20.0	14.5	4.0	2.9	465
Case5B	267.8	450	48.3	11.1	9.7	2.2	439
Case7B	209.9	462	36.9	19.4	7.4	3.9	443
Case5C	340.9	429	65.3	14.3	13.1	2.9	415
Case7C	265.9	455	43.1	30.3	8.6	6.1	424
Case8C	534.0	467	33.2	4.7	6.6	0.9	462

Table 4: *Energy production, losses, not produced energy due to failure, average power, capacity factor and levelized production costs*

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
Case1A	2408409	65779	12222	2.7	0.5	277	0.5532	0.0036
Case1A-NR	2368428	65744	52203	2.8	2.2	272	0.5440	0.0037
Case2A	2418329	54211	13881	2.2	0.6	278	0.5555	0.0038
Case2A-NR	2378177	54176	54032	2.3	2.3	273	0.5463	0.0039
Case5A	2289710	167408	28133	7.3	1.2	263	0.5259	0.0075
Case2B	2347694	104888	33367	4.5	1.4	270	0.5393	0.0084
Case4B	2310386	111531	63953	4.8	2.8	265	0.5307	0.0088
Case5B	2208536	229782	42493	10.4	1.9	254	0.5073	0.0098
Case7B	2224743	180302	78499	8.1	3.5	256	0.5110	0.0078
Case5C	2108443	304857	53499	14.5	2.5	242	0.4843	0.0132
Case7C	2150671	207250	119987	9.6	5.6	247	0.4940	0.0104
Case8C	2266948	200762	18289	8.9	0.8	260	0.5207	0.0188

Table 5: *Inductor size, max. output reactive and apparent power, annual hours of production, annual hours of no-production*

	Q_{induc} (MVA)	$Q_{out,max}$ (MVA)	$S_{out,max}$ (MVA)	Hrs_{wind} (hr/y)	Hrs_{nowind} (hr/y)
Case1A	5	88	487	7642	1065
Case1A-NR	5	88	487	7642	1065
Case2A	5	112	491	7642	1065
Case2A-NR	5	112	491	7642	1065
Case5A	NaN	0	466	7642	1065
Case2B	50	263	515	7591	1116
Case4B	100	426	582	7591	1116
Case5B	NaN	0	450	7642	1065
Case7B	NaN	0	462	7642	1065
Case5C	NaN	0	429	7642	1065
Case7C	NaN	0	455	7642	1065
Case8C	125	549	649	7432	1275

The number of hours wind and no wind is slightly different in the 500 MW cases. The number of hours wind is defined as the number of binned hours the wind farm output power is positive. This can be slightly different due to differences in the losses.

Table 6: *Voltage, current, power, reactive power, losses and relative losses at max wind speed*

	Voltage (kV)	Current (A)	Power (MW)	Reactive Power (Mvar)	Losses (MW)	Relative losses (%)
Case1A	149	1882	487	13	13	2.66
Case1A-NR	149	1882	487	13	13	2.66
Case2A	149	1901	490	43	10	2.08
Case2A-NR	149	1901	490	43	10	2.08
Case5A	106	2546	466	0	34	6.79
Case2B	147	2024	480	187	20	3.98
Case4B	239	1404	480	329	20	3.99
Case5B	102	2554	450	0	48	9.70
Case7B	194	1378	462	0	37	7.40
Case5C	97	2566	429	0	65	13.21
Case7C	191	1378	455	0	43	8.67
Case8C	146	2573	467	451	33	6.64

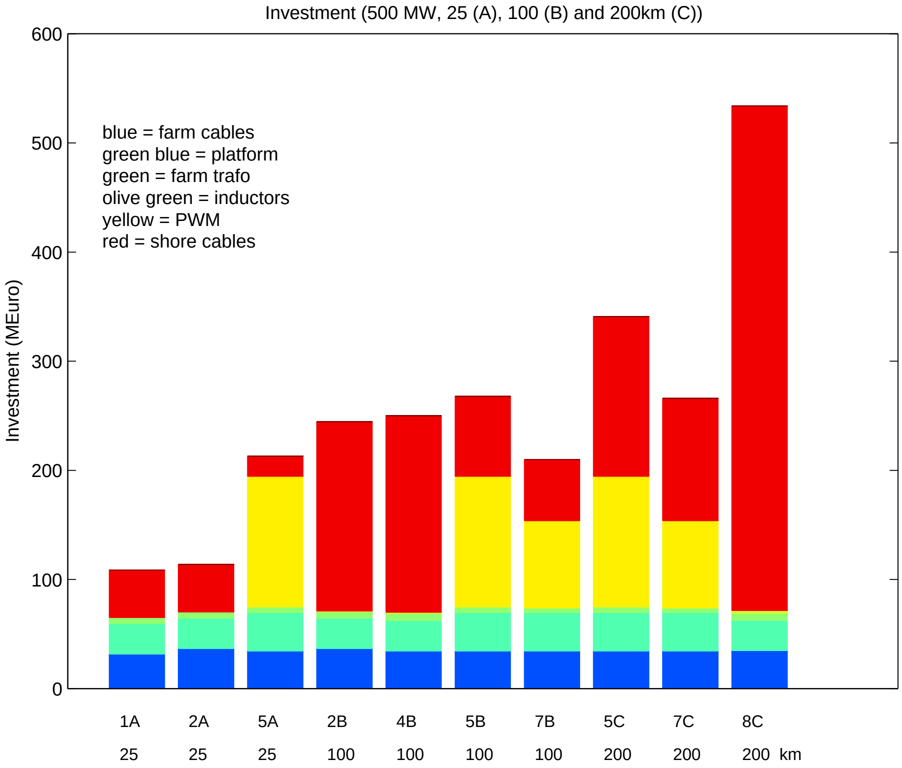

Figure 17: *Investment per component type for the 500 MW cases*

The investment costs per component type for the 500 MW cases are plotted in figure 17:

- cases with numbers ending on A are 25 km, B are 100 km and C are 200 km;
- the small differences in farm cable costs are caused by the voltage level (case 1A is 32kV, rest is 69kV) and different cable routes;
- the difference in investment cost of the farm trafo in case 2B and 4B is caused by a different voltage ratio: 66-150 and 66-245kV;
- the difference in inverter cost of case 5B and 7B is caused by different voltage level and number of converters;
- at 100 km, the investment costs of the AC cases 2B and 4B are in between the costs of the DC cases 5B (±80 kV) and 7B (±150 kV);
- at 200 km, the investment costs of the AC cases 8B are significantly higher than the costs of the two DC cases (5C and 7C).

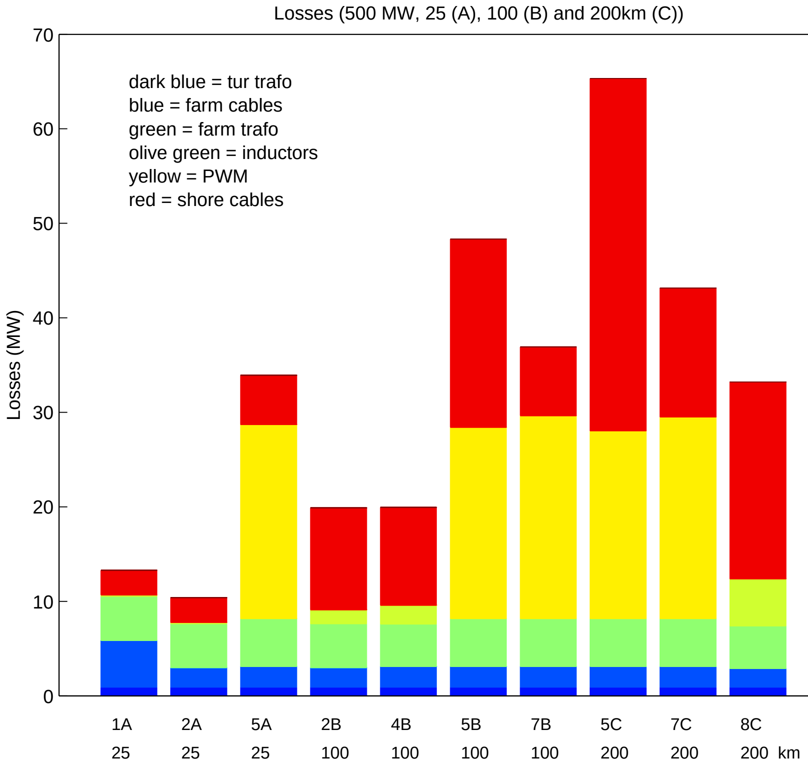

Figure 18: *Losses per component type at maximum power for the 500 MW cases*

The losses per component type at maximum power for the 500 MW cases are plotted in figure 18:

- the turbine transformer losses are included;
- for all cases, the farm transformer losses are more or less the same;
- the DC case losses (5A - 5B, 5C - 7B and 7C) are higher than the AC case losses at the same distance to shore (1A, 2A - 2B, 4B - 8C);
- the inductor losses are relatively high for the 200 km, 150 kV case (8C).

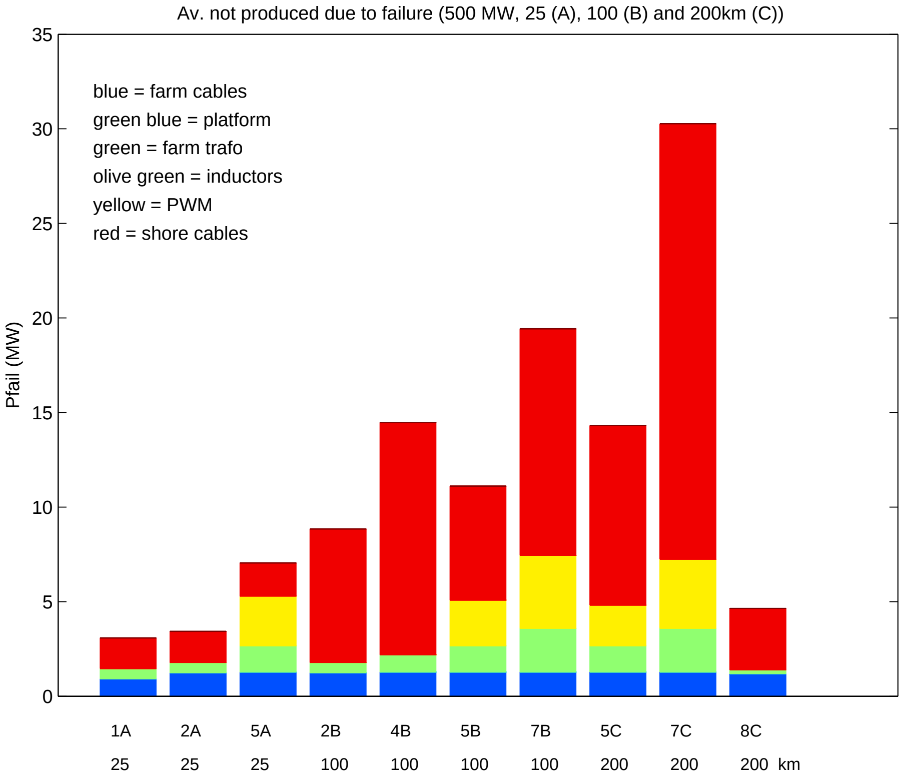

Figure 19: *Not produced power due to failure per component type at maximum power for the 500 MW cases*

The not produced power due to failure per component type at maximum power for the 500 MW cases are plotted in figure 19:

- the absolute values are uncertain due to the uncertainty of the component failure rates. Land cable failure rates are used and the repair time is estimated;
- the relative values between the cases depend less on failure rate accuracy, which is the same for all cases and more on the system choice, especially redundancy. The relative rating of the cases is therefore believed to be well represented;
- the not produced power due to converter failure in the cases 5A, 5B, 5C and 7B, 7C decreases due to higher losses;
- two aspects have a big effect on the not produced power due to failure of the shore cable: the length and the number of parallel cables: case 8 has four parallel cables, cases 1, 2 and 5 have three, case 4 has two while case 7 only has a single cable.

5 Wind farm cases @ 20MW, 1GW

5.1 Components and layouts

Turbine upscaling remarks:

- the turbine used is Variable Speed Pitch (VSP) with rated power P_{rated} = 20MW;
- the EeFarm Generic generator model is used.

The database contains data of 6 platforms:

- HVAC 30/130 kV - 120 MVA;
- HVAC 130 kV, 370-400 MW;
- HVDC (VSC) 150 kV - 370 MW;
- HVDC (VSC) 150 kV - 570 MW;
- HVDC (VSC) 300 kV - 1100 MW;
- HVDC (VSC) 2000 ton - 300 MVA.

Table 7: *Case matrix 1 GW*

Case nr.	16B	17B	18B	19C	17C	18C	17D	18D
Cable 33kV								
Cable 66kV	X	X	X	X	X	X	X	X
Dist 100 km	X	X	X					
Dist 200 km				X	X	X		
Dist 500 km							X	X
AC, 150 kV				X				
AC, 245 kV	X							
DC, 150kV		X			X		X	
DC, 300kV			X			X		X

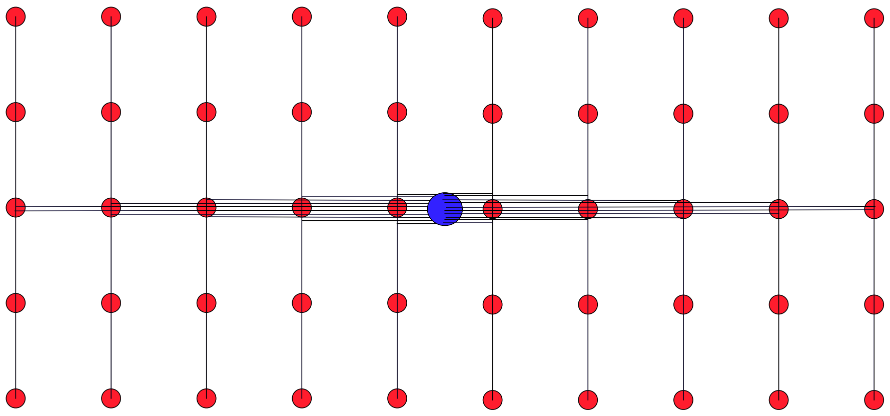

Figure 20: *Layout and cabling of 20MW - 1GW wind farm with 72kV, 58.4 MVA cables (nr. 26)*

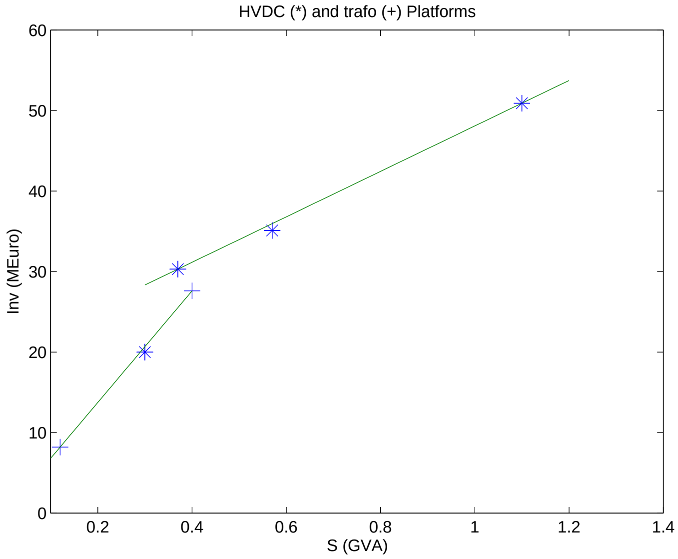

Figure 21: *Platform prices*

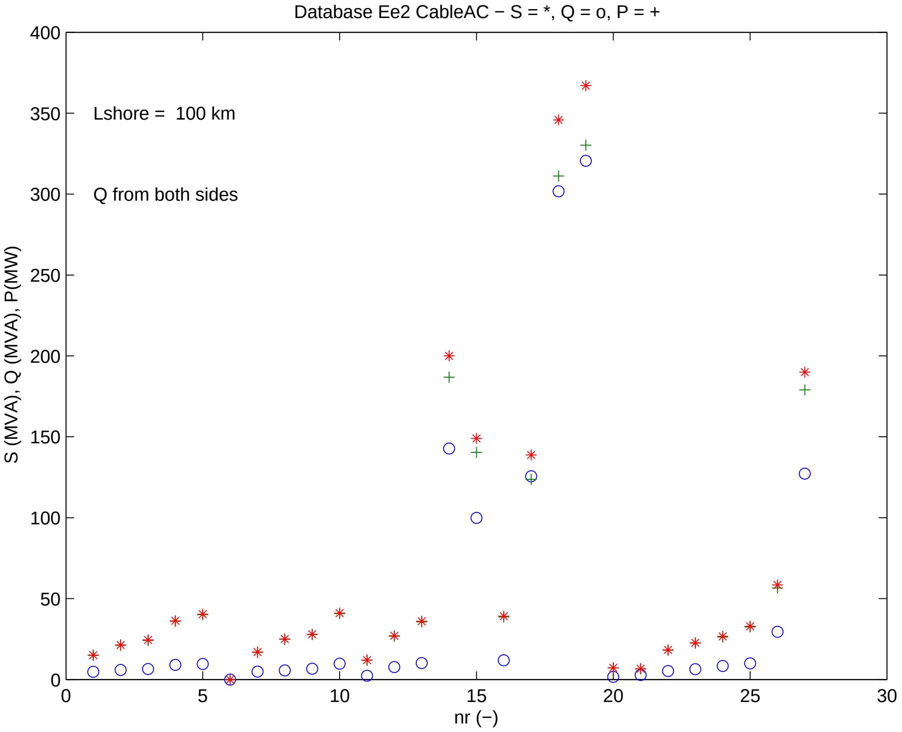

Figure 22: *AC cables - Q and maximum P for 100 km (P assumes equal Q compensation at both cable ends)*

Case 16 component choice:

Turbine and string cable choice:

- one 69kV cable in database: nr. 26, 58.4 MVA;
- database extended with five 72 kV cables with estimated electrical parameters (OH) and seven 72kV cables with electrical parameters but no price information (NKT);

- maximum power of OH cables is 106MVA (nr 5, A=630 mm^2) and of NKT cables respectively 98.5MVA (nr 12, A=800 mm^2);
- prices of the OH and NKT cables are estimated as follows: $Inv_{kEuro/km} = (0.4 + 0.7V_{kV})A_{mm^2}$, based on voltage and conductor size;
- due to the skin effect, the increase of the maximum current with increasing conductor area is relatively small and the (estimated) price of the 72kV cables with increasing power is relatively high, about the same as the total price of two cables 69kV with half the power;
- if two 69kV cables can be bundled and layed in one operation, the two cables solution gives about the same total price as a single cable with a two times higher rating;
- since the estimated power of cable nr.5 is high compared to the that of the even bigger NKT cable nr.12, and the price and size of the NKT cable nr. 12 is relatively unfavourable compared to two times cable nr. 26, the two cable solution will be used, with both cables operating in parallel. See figure 20 for the layout. A single cable nr.26 is used for the first two turbines and two parallel cables nr. 26 to connect all five turbines to the platform, see figure 20.

The implementation in EeFarm-II can be made in two ways:

- use two cable blocs in parallel with a splitter at cable input and a node at output;
- calculate a new (virtual) cable with equivalent parameters and price of the two parallel cables.

The first option has the advantage of keeping the wind farm model close to the physical reality. Only modification: half the laying costs (in initialisation routine). This option is chosen and implemented in a new model block *Cable AC double*. S_{redun} should still be 0 because both cables are in the same trench.

Other Case 16 components:

- a single transformer platform at the center of the wind farm will be used. For the price estimates see figure 21. Twice the price of a 400MVA traformer platform is taken, since 2.5 times would be rather high compared to the HVDC platform prices;
- figure 22 shows that for a 100 km cable to shore the highest rated power is 330 MW, reached with the 245 kV cable (nr. 19, S=367MVA Q=320MVA P=330MW). So three parallel cables nr. 19 are sufficient. If a 150kV cable is used, the options are nr. 14 (S=200MVA Q=143MVA P=187MW) or nr. 27 (S=190MVA Q=127MVA P=179MW). In both cases 6 cables are required. The 245 kV cable nr. 19 will be used.

Case 17 component choice:

- the cables and the cable routing inside the farm are same as in case 16 (see figure 20);
- a 150 kV bipolar DC connection to shore will be used, five parallel 150 kV - 200 MW systems;
- a single transformer platform at the center of the wind farm will be used. For the price estimates see figure 21. The price estimate of a 1GW HVDC platform is used;

Case 18 component choice:

- the cables and the cable routing inside the farm are same as in case 16 and 17 (see figure 20);
- a 300 kV bipolar DC connection to shore will be used, two parallel 300 kV - 500 MW systems;

- same platform as case 17;

Case 19 component choice:

- the cables and the cable routing inside the farm are same as in case 16, 17 and 18 (see figure 20);
- for 200 km the AC connection to shore, the same choice is made as in as Case 8 (cable nr. 27, 150kV, 190MVA), times two, so 8 cables;
- at 200 km, the 245kV cable reactive power is too high to have an advantage over the 150kV cable (the maximum power of both cables is about the same, see figure 16, but the 245kV cable is more expensive;
- a 500km AC connection is not feasible anymore, since for this distance the 150kV cable reactive power will surpass two times the cable apparent power (see figure 16, with Q multiplied by 2.5). This can only work with a half way reactive power compensation (and a half way platform), which will not be considered in this study.

Table 8: Component matrix 1 GW cases

	Case 16				Case 17				Case 18				Case 19			
	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.	DB	kV	MVA	nr.
Turbine	-	4	20	50	idem				idem				idem			
Tur trafo	T	69	25	50	idem				idem				idem			
Tur cable	26	69	58	40	idem				idem				idem			
String cable	26	69	58	20	idem				idem				idem			
Farm trafo	T	245	350	3	T	107	200	5					T	150	150	
Inductor	I	245	162	3									I	150	125	
Farm cable	19	245	367	3									27	150	190	8
PWM conv					2	80	200	5	5	150	500	2				
Farm DC cable	19	245	367	3	5	80	200	5	13	150	537	2				

DB: component number in database, T: transformer p.u. parameters, I: inductor p.u. parameters

5.2 Results 1 GW

Table 9: *Investment costs and power (at max wind speed)*

	Inv (MEuro)	$P_{out,max}$ (MW)	$P_{loss,max}$ (MW)	$P_{fail,max}$ (MW)	$P_{loss,max}$ (%)	$P_{fail,max}$ (%)	$P_{nett,max}$ (MW)
Case16B	417.1	956	43.6	20.1	4.4	2.0	936
Case16B-NR	417.1	956	43.6	63.6	4.4	6.4	893
Case17B	479.2	902	95.2	5.3	9.5	0.5	897
Case18B	376.8	924	74.5	14.7	7.4	1.5	909
Case19C	1046.5	932	67.8	2.6	6.8	0.3	930
Case17C	619.7	863	136.7	4.2	13.7	0.4	859
Case18C	488.8	909	86.9	20.7	8.7	2.1	888
Case17D	1041.4	746	253.4	4.2	25.3	0.4	742
Case18D	824.8	863	114.8	27.7	11.5	2.8	836

Table 10: *Energy production, losses, not produced energy due to failure, average power, capacity factor and levelized production costs*

	E_{tot} (MWh/y)	E_{loss} (MWh/y)	E_{fail} (MWh/y)	$E_{lossrel}$ (%)	$E_{failrel}$ (%)	P_{av} (MW)	CF (-)	LPC (Euro/kWh)
Case16B	4662425	233210	76186	5.0	1.6	535	0.5355	0.0072
Case16B-NR	4422862	232944	315749	5.3	7.1	508	0.5080	0.0081
Case17B	4487255	454617	21811	10.1	0.5	515	0.5154	0.0085
Case18B	4548799	364162	54957	8.0	1.2	522	0.5224	0.0067
Case19C	4552414	407478	13145	9.0	0.3	523	0.5228	0.0182
Case17C	4324177	629522	18379	14.6	0.4	497	0.4966	0.0114
Case18C	4464000	419428	74783	9.4	1.7	513	0.5127	0.0089
Case17D	3824654	1129049	18375	29.5	0.5	439	0.4393	0.0217
Case18D	4246861	548452	97002	12.9	2.3	488	0.4878	0.0158

Table 11: *Inductor size, max. output reactive and apparent power, annual hours of production, annual hours of no-production*

	Q_{induc} (MVA)	$Q_{out,max}$ (MVA)	$S_{out,max}$ (MVA)	Hrs_{wind} (hr/y)	Hrs_{nowind} (hr/y)
Case16B	162	525	1005	7591	1116
Case16B-NR	162	525	1005	7591	1116
Case17B	NaN	0	902	7642	1065
Case18B	NaN	0	924	7642	1065
Case19C	125	1085	1291	7432	1275
Case17C	NaN	0	863	7642	1065
Case18C	NaN	0	909	7642	1065
Case17D	NaN	0	746	7642	1065
Case18D	NaN	0	863	7642	1065

- in Case 19C $S_{out,max}$ is relatively low compared to $Q_{out,max}$. This can be explained if these are not coinciding. For a increasing power, the wind farm transformers produce additional reactive power, which decreases Q_{out} from 1085 MVA at zero power to 900 MVA at maximum power;

Table 12: *Voltage, current, power, reactive power, losses and relative losses at max wind speed*

	Voltage (kV)	Current (A)	Power (MW)	Reactive Power (Mvar)	Losses (MW)	Relative losses (%)
Case16B	242	2395	956	310	44	4.36
Case16B-NR	242	2395	956	310	44	4.36
Case17B	103	5073	902	0	95	9.55
Case18B	194	2751	924	0	74	7.46
Case19C	146	5123	932	894	68	6.78
Case17C	98	5072	863	0	137	13.67
Case18C	191	2751	909	0	87	8.73
Case17D	85	5068	746	0	253	25.35
Case18D	181	2750	863	0	113	11.56

- in Case 17D the AC converter voltage is relatively low compared to case 17B due to the high losses and voltage drop in the 80kV, 500km DC cable.

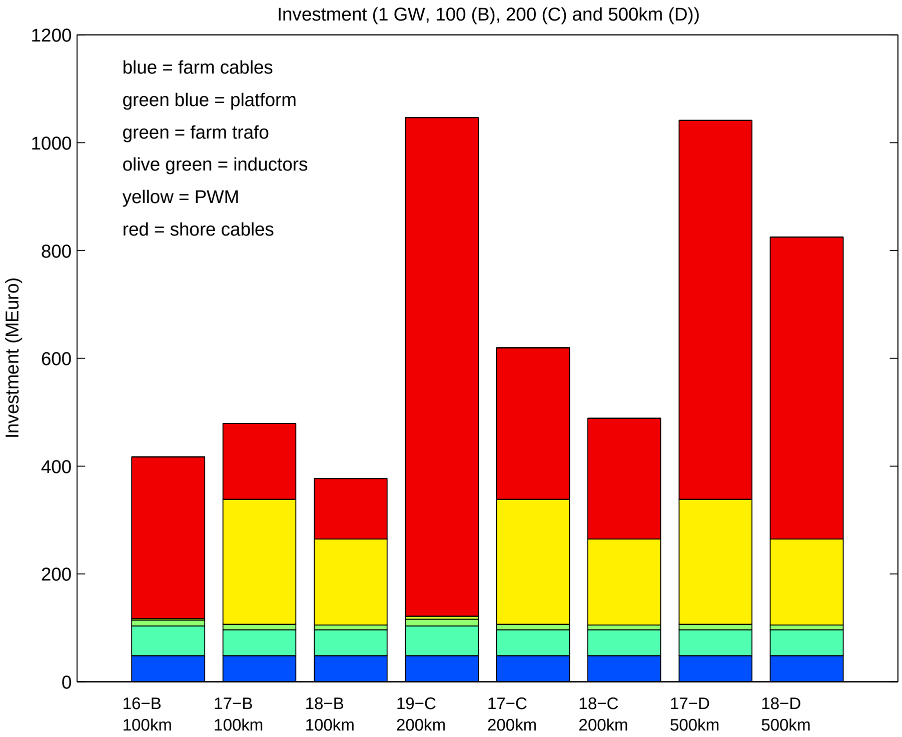

Figure 23: *Investment costs per component type for the 1GW cases*

The investment per component type for the 1GW cases are plotted in figure 23:

- the investment costs for farm cables are the same for all 1GW options;
- the investment costs for platforms differ slightly between AC and DC systems;
- the investment cost for case 16B, 17B and 18B (100 km) are in the same range;
- the shore cable investment costs are very high in Case 19C, due to the number of parallel connections (8) required for 1GW at 200 km;
- increasing the distance in the DC cases correspondingly increases the cable to shore investment costs: 17B, 17C, 17D and 18B, 18C, 18D;
- increasing the DC voltage decreases the investment costs for a 1GW system.

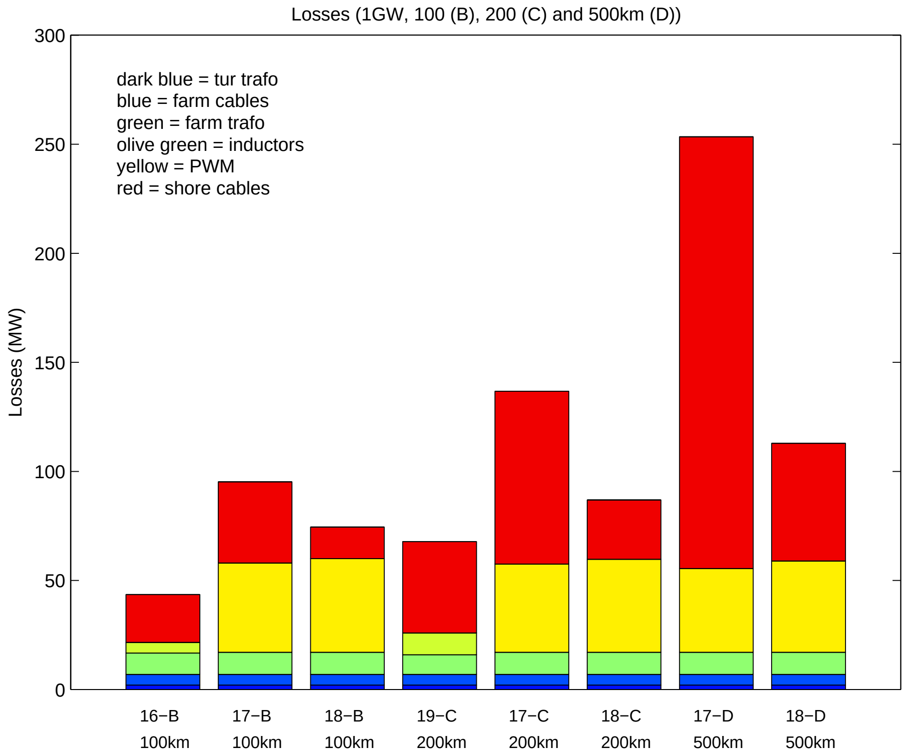

Figure 24: *Losses per component type at maximum power for the 1GW cases*

The losses at maximum power per component type for the 1GW cases are plotted in figure 24:

- the converter losses are a substancial part of the total losses;
- at 100 km, the ±80kV DC cable losses are higher than the 245kV AC cable losses (Case 16B and 17B);
- increasing the DC voltage to ±150kV increases the converter losses a little but decreases the DC cable losses a lot (Case 17B vs. 18B, 17C vs. 18C and 17D vs. 18D);
- at 200 km, the AC system (now at 150 kV) still produces lower losses than the two DC systems;
- contrary to AC cables, the DC cable losses scale linearly with the distance: 17B - 17C - 17D and 18B - 18C - 18D;
- the losses in case 17D (±80kV, 500km) appear to be too large to be acceptable.

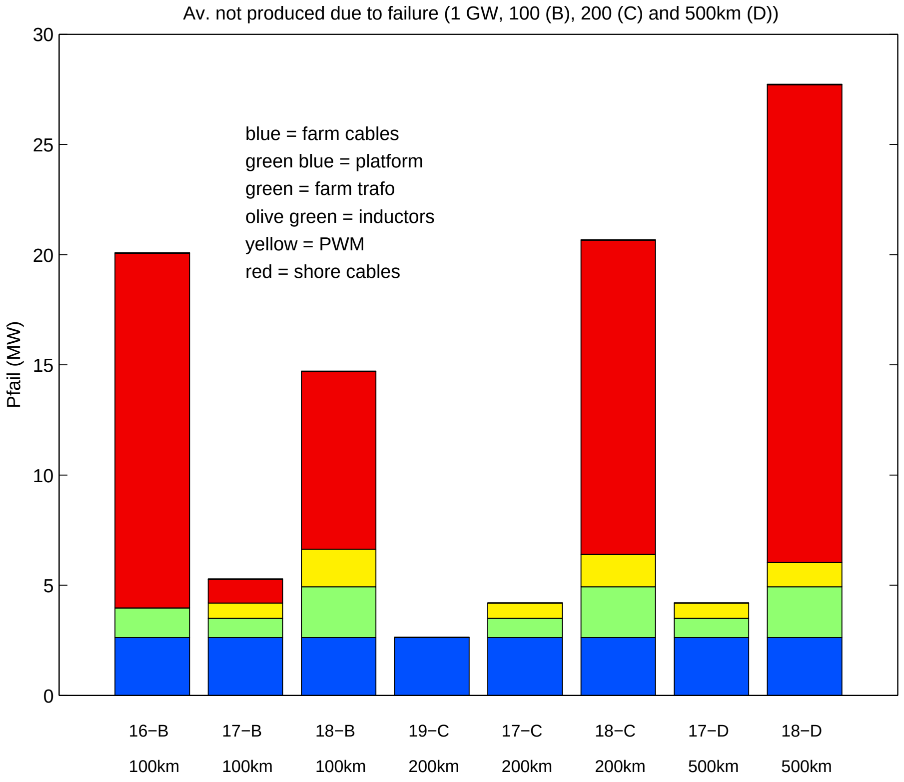

Figure 25: *Not produced power due to failure per component type at maximum power for the 1GW cases*

The power not produced due to component failure at maximum power per component type for the 1GW cases is plotted in figure 25:

- as mentioned before, the absolute values have a high uncertainty. The relative difference between the cases are considered to be more significant, since these are caused by differences in redundancy;

- the cabling inside the farm is the same for all cases, so here is no difference in power not produced due to failure between the cases;

- differences in power not produced due to failure for the transfomers (green) and converters (yellow) result from the number of parallel units;

- for Cases 16B, 17B and 18B the number of parallel cables to shore is 3, 5x2 (bipolar) and 2x2 (bipolar) respectively, this explains the observed differences. So for Case 17B S_{redun} is 90% of the rated power and the failure of a single cable only leads to an average power loss of about 1 MW (0.1% of full power);

- Case 17C has a zero not produced power due to cable failure. This appears to be a strange result since the system is the same as 17B, except for the distance to shore (100 and 200km). For Case 17C however, the losses are higher (see figure 24). Therefore, the redundancy power level is not passed in Case 17C. This is also true for case 17D (500km);

- Case 19C is connected to shore by 8 parallel AC cables. The losses at max. power are about 14 MW (about 7%). The 8 parallel AC cables give an S_{redun} of 87.5%. Therefore, a non zero not produced power due to cable failure is expected, which is not the case. So the losses alone can not explain zero not produced power due to cable failure. The reactive power decreases with increased power and this explains not surpassing the 87.5% threshold. Secondly, S_{redun} of a component is specified with respect to the rated apparent power of that component, which need not be reached if the component is slightly overdimensioned. In the DC connections, the apparent power effect is absent, of course;

- increased losses also explain that the not produced power due to cable failure does not increase linearly with the distance when comparing DC cases 18B, 18C and 18D.

6 Conclusions and recommendations

This report present the results of a comparison of the electrical systems for two large wind farms (500 MW and 1 GW) and two turbine sizes (5 and 20 MW). The comparison includes systems with AC and DC connections to shore and distances to shore of 25, 100, 200 and 500 km. The EeFarm-II program for wind farm electrical and economic evaluation has been used to determine the voltages, currents, active and reactive power of each component in the farm for each wind speed bin in the operating range of the turbines. The losses, power not produced due to component failure, investment costs have been calculated, not only for the total electrical system but also per component type, to be able to compare and check the results. A database with component parameters and recent budget prices has been used. After assuming a wind speed distribution, the annually produced energy has been determined, followed by the levelized production costs (LPC).

For the 500MW wind farm ten electrical systems (cases) have been evaluated, five use an AC connection to shore and five a DC connection. For the 1 GW wind farm eight electrical systems (cases) have been evaluated, two use an AC connection to shore and six a DC connection. The component choice for each case has been motivated. The total produced power, produced energy, losses, not produced energy due to component failure, investment costs, LPC and a number of electrical variables have been compared. Investment costs, losses and not produced energy due to component failure have also been presented and discussed per component type.

Upscaling aspects in this study have been: the wind farm size (500MW and 1GW), the wind turbine size (5 and 20 MW) and the distance to shore (25, 100, 200 and 500 km).

Table 13: *Wind farm categories and preferred cases*

Farm size MW	distance to shore km	case with lowest LPC	voltage and type
500	25	1A	32kV AC, 150kV AC
500	100	7B	69kV AC, ±150kV DC
500	200	7C	69kV AC, ±150kV DC
1000	100	18B	69kV AC, ±150kV DC
1000	200	18C	69kV AC, ±150kV DC
1000	500	18D	69kV AC, ±150kV DC

Trends in upscaling and reliability effects:

- increasing the wind farm size leads in some cases to an unpractical number of cables, for example eight (1GW, 150kV AC) to ten (1GW, ±80kV DC, bipolar). See table 2 and 8;
- at 500 km a low transport voltage (±80kV DC) leads to unacceptable high losses (25%). See figure 24;
- at distances above 200km the reactive power of the AC cable limits the maximum active power to an unacceptable low level. See figure 16;
- a turbine size of 20MW requires high voltage and high ampacity cables to prevent cable spagetti inside the wind farm;
- the ±80kV DC system was never the preferred system for the six wind farm categories (see table 13);
- the 245kV AC system was never the preferred system for the six wind farm categories either (see table 13);
- component failure can have a significant effect on the produced energy and the LPC of the wind farm. Although the reliability data (failure rates and repair times) for offshore

wind farm components are still unreliable due to a lack of failure statistics for most of the components under offshore operating conditions, comparison of the cases shows that there can be large differences in the not produced power due to component failure. Parallel components and redundancy therefore play a role in the determination of the LPC. Large systems, which require (sometimes many) parallel connections to shore, have a clear advantange here. In some of the 1 GW wind farm cases the failure of one of the connections to shore did not influence to produced energy at all. See figure 25.

Recommendations:

- in this study, only a single wind farm with a single connection to shore has been investigated. If several large wind farms are installed in for instance the North Sea, it makes sense to investigate transnational offshore grids to connect these farms. Major advantages are electric power trade between national markets, hydro power storage, increasing electrical system reliability, controlability and stability;
- transnational grids require a high investment and benefit from a modular step by step building process, growing organically with the development of large offshore wind farms;
- due to the large distances, transnational grids require DC connections;
- DC connections have relatively limited ratings and operating these connections in parallel or in multiterminal mode would make these connections more flexible and feasible in a modular building process;
- in this study, the focus has been on electical losses, component failure and investment costs, culminating in the LPC. In this way, some of the positive and negative aspects of electrical system of large wind farms have been left out of the evaluations. For instance dynamic and control aspects of the different systems, harmonics and effects on the national grid. To include these aspects a different approuch is required, for instance multiobjective optimization. It is recommended to develop this method.

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A EeFarm II introduction

In 2001, ECN and TU Delft have developed the EeFarm program for the electrical and economic evaluation of different electrical layouts and concepts for Offshore Wind Farms [9]. EeFarm calculates the voltages, currents, powers, reactive powers and electric losses for each node of a given wind farm and for each wind speed and wind direction. It uses these to determine the anually produced energy and the costs per generated MWh. Since voltages and currents are calculated for each component in the wind farm and for each wind speed and wind direction bin, an accurate calculation of electrical performance of the farm is possible. The programme can be used to make an estimate of the production cost of a proposed wind farm and to study the effect of different electrical system layouts and concepts on these production costs.

The version of EeFarm made in 2001 consists of a number of Matlab routines, one or more for each type of electrical component. For each wind farm concept, a wind farm layout dependent program has to be written by the user that calls the component routines. Matlab command lines have to be programmed for each individual component, the in- and output signals have to be connected in the correct way and the correct component parameters have to be loaded. The creation or modification of the calling program has to be repeated each time the wind farm layout or components are changed. This is a time consuming process and a cause of errors. The major drawback of the 2001 version of EeFarm is its user-unfriendly-ness.

To solve this problem, the EeFarm II project was defined as part of the we@sea consortium. The main project objective is [6]:

Development and demonstration of a user friendly second version of the EeFarm computer program for wind farm electrical layout and optimization.

EeFarm has been re-program entirely, resulting in a user friendly, easy to use analysis and optimisation tool for wind farm developers. This was achieved by converting EeFarm to a graphically based user interface, viz. Simulink. In the process, EeFarm has been extended with missing component models and updated and improved where needed. EeFarm II has been tested and evaluated by ECN and Vattenfall. This report describes the results.

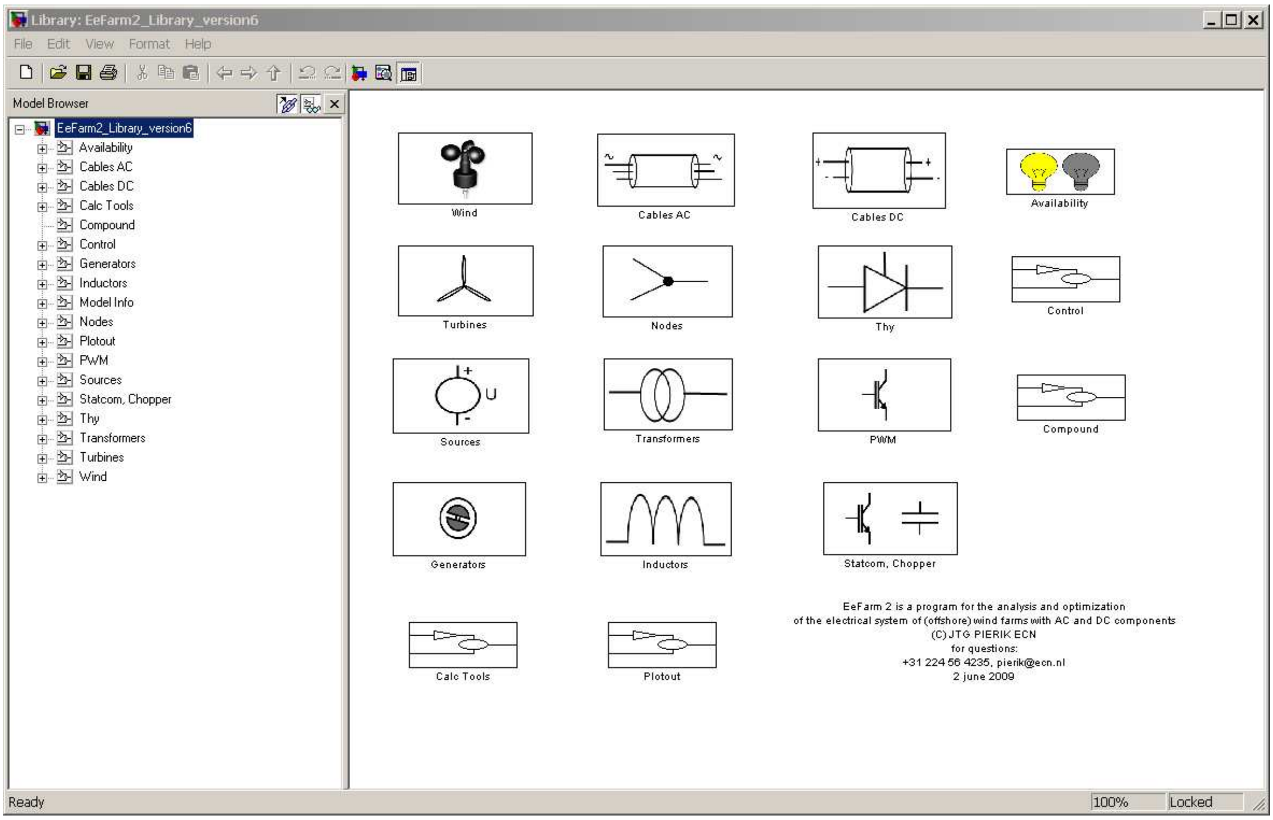
The EeFarm program incorporates the following aspects:

- wind speed (and wind direction) dependent calculation of:
    - turbine power production, including the effect of the location of the turbine in the farm (wind speed deficit in wake);
    - voltage and current phasor at each wind farm component input and output (turbine, transformer, cable, converter);
    - electric losses per component;
    - wind farm power production;
- estimation of the effect of component failure on the power production, based on component failure rates and repair time;
- a database with component electrical parameters and component costs;
- wind farm annual energy production, based on the wind speed distribution;
- wind farm production cost (Euro/kWh).

The voltages and currents will not be calculated iteratively to reduce the simulation time (one run includes hundreds of components and hundreds of wind speed and wind direction bins). The effect of this approximation on the currents, voltages and electrical losses is relatively small. The amplitude and rotation of the voltage phasor at the grid connection can be used to as a check. Under normal circumstances the maximum voltage difference the wind farm (from wind turbine to point of grid connection) is expected to be a few percent. The difference between the exact and the approximated voltage and current will be a fraction of this value. Therefore, the error in the power losses due to the non-iterative solution is expected to be less than one percent.

B EeFarm II description

The core of EeFarm II consists of steady state models of electrical components, AC as well as DC, and simple steady state models of different types of wind turbines. The EeFarm component models reside in a Simulink model library, see figure 26. A wind farm model is built by copying the model blocs to a Simulink model and connecting the models. The electrical blocs have one input and one output signal, which is a Simulink bus signal. See table 14 for the contents of this bus signal. The signal direction is from the individual wind turbine in the direction of the point of common coupling (PPC: the connection of the wind farm to the HV grid). So, for example, the cable side connected to the turbine generator is called *in* and the side connected to the turbine transformer is called *out*. The signal direction also shows the order in which the model blocks are evaluated, starting at the turbines and ending at the HV transformer at the PCC. The voltage at each wind turbine generator is set by the user and is assumed to be constant, all other voltages are calculated by the programme. If two outputs need to be joined, for instance two cables comming from two turbines, a node block is used. Table 15 gives an overview of the components in the library of EeFarm II.



EeFarm 2 is a program for the analysis and optimization
of the electrical system of (offshore) wind farms with AC and DC components
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2 june 2009

Figure 26: *EeFarm model library*

Table 14: Bus signals

$U_{line,out}$	line voltage phasor (RMS) at component output, complex number	(V)
$I_{phase,out}$	current phasor (RMS) at component output, complex number	(A)
P_{out}	power at component output	(W)
Q_{out}	reactive power at component output	(VA)
$P_{in} - P_{out}$	component losses	(W)
$Q_{in} - Q_{out}$	reactive power produced by component	(VA)
$\sum(P_{in} - P_{out})$	sum of component losses	(W)
f	frequency	(Hz)
$\sum Invcost$	sum of component investment costs	(kEuro)
P_{fail}	power not produced due to component failure	(W)
$\sum P_{fail}$	sum of power not produced due to component failure	(W)

Table 15: Overview of EeFarm II components

Model	Simulink block	Remarks
Wind	Wind	wind input block
	GCL	Simulink implementation of GCL model
Turbine	Turbine internal curve	single P(V) curve or FyndFarm or FluxFarm input
	Turbine WF eff.	VSP, CSP or CSS turbine, lookup table GCL preprocessor
	VSP turb	single P(V) curve or FyndFarm or FluxFarm input
Generator	Generator Generic	type independent simple generator model
	IM stat	directly connected induction machine
	DFIG	doubly fed induction machine
	FCIM	induction machine with full converter
	FCSM	synchronous machine with full converter
Transformer	TrafoQ	AC transformer with reactive power calculation
	Trafo Noloss Nofail	AC transformer, only the transformer ratio
Cable	CableAC	constant temperature π cable model
	CableDC	constant temperature, earth return DC cable
	CableDCbipolar	constant temperature, bipolar DC cable
Node	NodeAC	connects two AC bus signals
	NodeDC	connects two DC bus signals
	SplitterAC	splits an AC bus signal
	SplitterDC	splits a DC bus signal
Inductor	InductorQ	fixed size inductor for reactive power compensation
Thy	Thy rect	thyristor rectifier
	Thy inv	thyristor inverter
PWM	PWM rect Kaz	IGBT rectifier Kazmierkovski model
	PWM inv Kaz	IGBT inverter Kazmierkovski model
	PWM rect TUD	IGBT rectifier TUD model
	PWM inv TUD	IGBT inverter TUD model
	PWM rect Inf	IGBT rectifier Infineon model
	PWM inv Inf	IGBT inverter Infineon model
Chopper	Step-up chopper	DC-DC transformer
Statcom	Statcom TUD	IGBT inverter TUD model modified as Statcom
Availability	Availability	power reduction due to component failure
Control	Qfeedback	sets the reactive power of individual turbines

The input for a EeFarm calculation is either the wind speed or the power of each individual wind turbine in the farm. In the first case, the EeFarm model includes turbine, turbine generator, turbine cable and turbine transformer models. In the second case it uses the wind turbine power curve specified by the turbine manufacturer and turbine generator, turbine cable and turbine transformer models are only required if the reactive power produced by the turbine has to be determined. Then the losses in these components are set to zero. In the second case, the power of each individual wind turbine in the farm, calculated by a wind farm wake program (for instance the ECN programs FyndFarm or FluxFarm) can be used. Figure 27 gives an overview of the different steps in the calculation of the Levilised Production Costs.

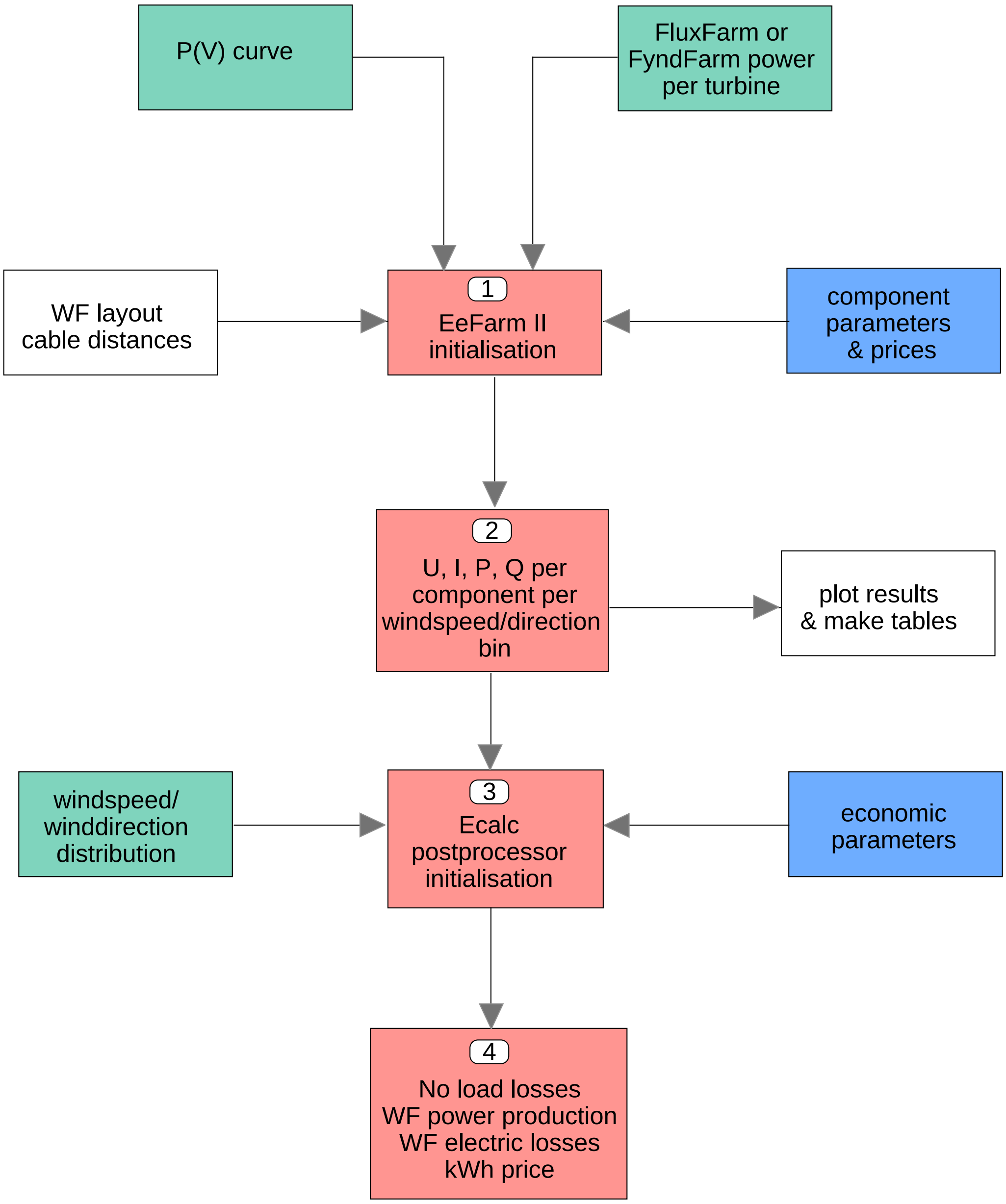

Figure 27: *EeFarm II model overview*

EeFarm-II includes a database with electrical parameters and costs of the components in wind farms. A wind farm specific m-file reads the required parameters from the database and fills the component specific parameters structures used in the EeFarm-II component model library. The EeFarm model parameters are passed to the simulation using a mask. This enables the use of different sets of parameters for one and the same library block [3].

The next sections describe the component models. For each model, the input, the output and the parameters are listed. This is followed by the model equations and a look inside the corresponding Simulink block.

C EeFarm-II parameter database

The database is a crucial part of the EeFarm-II program. For each component, the database contains a number of options, especially for different component sizes. Then a user can choose the component from the database which is best suitable for his application. The entries in the database are based on data obtained from component manufacturers. Some of the parameters are copied one on one from the information supplied by manufacturers, in other cases the manufacturer data did not fit the EeFarm-II requirements directly and had to be recalculated and sometimes approximations had to be applied. All parameters, including the investment costs, are based on data supplied by manufacturers, with the exception of failure data and repair time, which was not supplied by manufacturers.

C.1 Component parameter list

Turbine	Manufacturer		
	Type	for example: NM1500	
	S_{nom}	rated apparent power	(MVA)
	D	diameter	(m)
	Control	for instance: constant speed stall	
	P(V)	power-wind speed table	
	P(n)	power-rotor speed table [1]	
	Cdax(V)	thrust coefficient-wind speed table[2]	
	$Invcost$	turbine investment cost	(kEuro)
	$Instcost$	installation cost	(kEuro)
Generic generator	η	efficiency	(-)
	$Invcost$	investment cost	(kEuro)
Induction generator	Manufacturer		
	Type	for example:	
	U_{nom}	rated rms line voltage	(kV)
	S_{nom}	rated apparent power	(MVA)
	l_s, l_m, l_r	stator leakage, mutual, rotor leakage inductance	(H)
	r_s, r_r	stator, rotor resistance	(Ω)
	$Invcost$	investment cost	(kEuro)
DFIG	Manufacturer		
	Type	for example:	
	U_{nom}	rated rms line voltage	(kV)
	S_{nom}	rated apparent power	(MVA)
	l_s, l_m, l_r	stator leakage, mutual, rotor leakage inductance	(H)
	r_s, r_r	stator, rotor resistance	(Ω)
	pp	number of pole pairs	(-)
	$Invcost$	investment cost	(kEuro)
AC cable	Manufacturer		
	Type	for example: XLPE, Cu-1x3x240	
	U_{nom}	rated rms line voltage	(kV)
	S_{nom}	rated apparent power	(MVA)
	A	area of cross section of conductor	(mm^2)
	f	frequency	(Hz)
	C	capacitance	(F/km)
	$R_{ac,20}, R_{ac,90}$	frequency dependent part of resistance	(Ω/km)
	$R_{dc,20}, R_{dc,90}$	frequency independent part of resistance	(Ω/km)
	L	inductance	(H/km)
	$\tan\delta$	dielectric loss factor	(-)
	$Invcost$	cable investment cost	(kEuro/km)
	$Instcost$	cable laying cost	(kEuro/km)

[1] for variable speed turbine; [2] for GCL model;

Transformer	Manufacturer		
	Type	for example: three way transformer	
	U_{lo}	rated rms line voltage LV side	(kV)
	U_{hi}	rated rms line voltage HV side	(kV)
	S_{nom}	rated apparent power	(MVA)
	$Ploss_{fl}$	full load losses	(kW/MVA)
	$Ploss_{nl}$	no load losses	(kW/MVA)
	R_{lo}	resitance LV side	(Ω)
	R_{hi}	resitance HV side	(Ω)
	L_{lo}	leakage inductance LV side	(H)
	L_{hi}	leakage inductance HV side	(H)
	L_m	mutual inductance side	(H)
	$Invcost$	investment cost	(kEuro)
	$Instcost$	installation cost[1]	(kEuro)
Inductor	Manufacturer		
	U	rated rms line voltage side	(kV)
	S_{nom}	rated apparent power	(MVA)
	L	inductance	(H)
	R_{cu}	ohmic resistance	(Ω)
	R_{fe}	equivalent magnetizing resistance	(Ω)
	$Invcost$	investment cost	(kEuro)
	$Instcost$	installation cost[1]	(kEuro)
DC cable	Manufacturer		
	Type	for example: XLPE, Cu-1x3x240	
	U_{nom}	rated rms line voltage	(kV)
	P_{nom}	rated apparent power	(MW)
	A	area of cross section of conductor	(mm^2)
	$R_{dc,20}, R_{dc,90}$	resistance	(Ω/km)
	$Invcost$	cable investment cost	(kEuro/km)
	$Instcost$	cable laying cost	(kEuro/km)
Thyristor rectifier	Manufacturer		
	Type		
	$U_{ac,nom}$	rated rms line voltage	(kV)
	$U_{dc,nom}$	rated DC voltage at zero firing angle	(kV)
	S_{nom}	rated apparent power	(MVA)
	E_0	thyristor threshold voltage	(V)
	R_{on}	thyristor resistance in on state	(Ω)
	$Invcost$	investment cost	(kEuro)
	$Instcost$	installation cost[1]	(kEuro)
Thyristor inverter		same as thyristor rectifier	

[1] this may include platform investment and installation cost

PWM rectifier	Manufacturer		
	Type		
	U_{ac}	rated rms line voltage	(kV)
	U_{dc}	DC voltage	(kV)
	S_{nom}	rated apparent power	(MVA)
	E_0	threshold voltage	(V)
	R_{on}	internal resistance	(Ω)
	F_s	IGBT switching frequency	(Hz)
	T_{on}	time needed to switch on an IGBT	(s)
	T_{off}	time needed to switch off an IGBT	(s)
	$Invcost$	investment cost	(kEuro)
	$Instcost$	installation cost[1]	(kEuro)
PWM inverter		same as PWM rectifier	
Step up chopper	Manufacturer		
	Type		
	U_{lo}	DC voltage LV side	(kV)
	U_{hi}	DC voltage HV side	(kV)
	S_{nom}	rated apparent power	(MVA)
	E_0	threshold voltage	(V)
	R_{on}	internal resistance	(Ω)
	F_s	IGBT switching frequency	(Hz)
	T_{on}	time needed to switch on an IGBT	(s)
	T_{off}	time needed to switch off an IGBT	(s)
	$Invcost$	investment cost	(kEuro)
	$Instcost$	installation cost[1]	(kEuro)
Wind Farm	TOM	wind farm operation and maintenance cost	(Euro/kWh)

[1] this may include platform investment and installation cost

C.2 Database implementation

For the EeFarm II database the Matlab structure format has been used [2]. Each component type is represented by a numbered structure, i.e. DB.turb(n).xxx or DB.rectPWM(n).xxx, with xxx the parameter name, i.e. R_{on} or $Invcost$, corresponding to the parameters of the component in the list in section C.1. At the start of each simulation, EeFarm-II runs a Matlab initialisation file, which specifies which component parameters will be used in the simulation.

Sets of component parameters, for instance the parameters of all components in a turbine, are loaded into a new structure, named *turb*. in order to reduce the number of changes that have to be made for each occurence of the block in the Simulink model. In case of a turbine, the length of the cable connecting the turbine to the next turbine and sometimes the cable type will be different. Since the turbine block is masked, by changing the name under the mask in the simulation model, the location specific parameters are transmitted.

D Database info

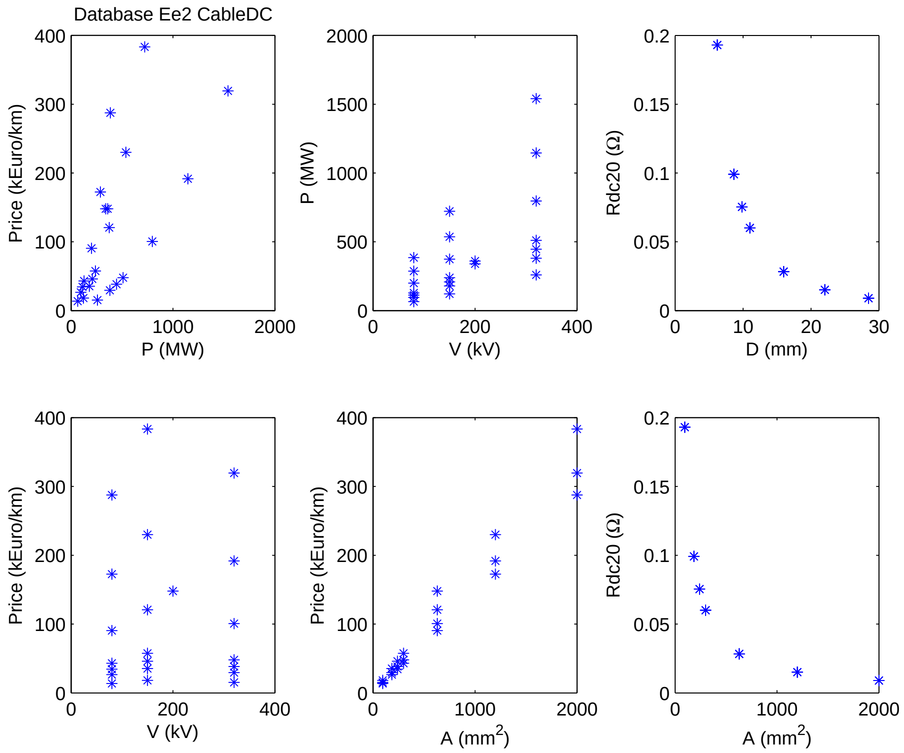

Figure 28: *DC cables in database*

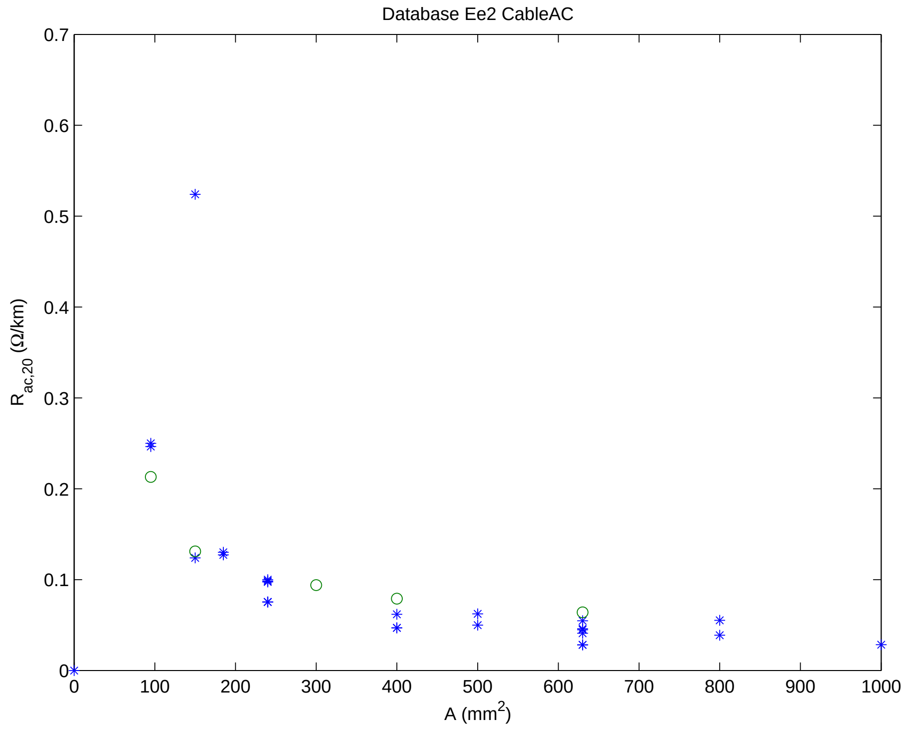

Figure 29: *AC cables in database*

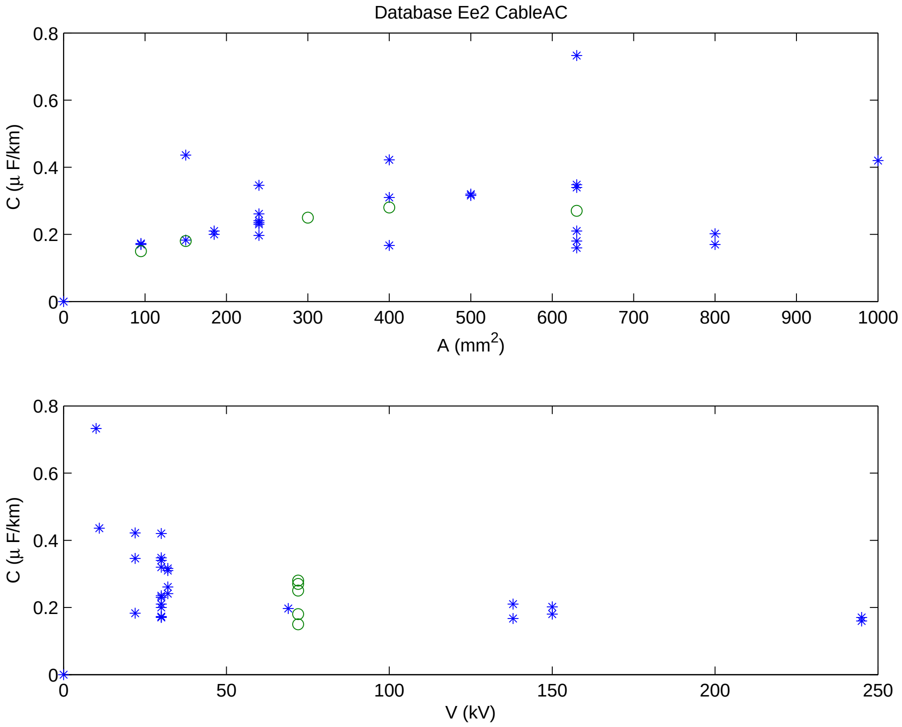

Figure 30: *AC cables in database*

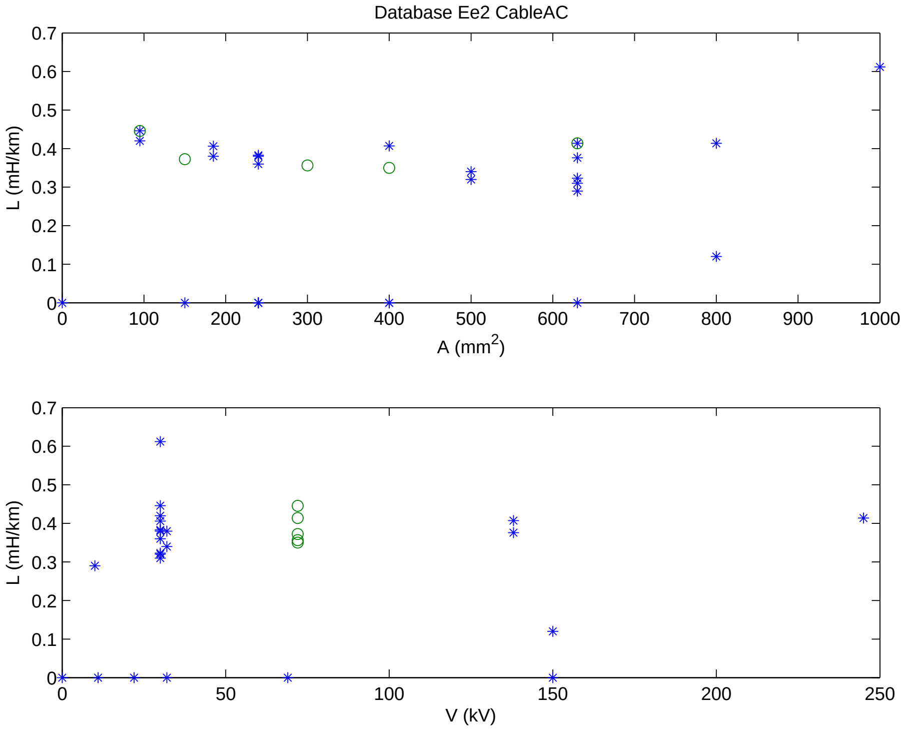

Figure 31: *AC cables in database*