*Energies* **2010**, *3*, 619-633; doi:10.3390/en3040619

OPEN ACCESS

*energies*

**ISSN 1996-1073**

www.mdpi.com/journal/energies

*Article*

# A Wind Farm Electrical Systems Evaluation with EeFarm-II

**Jan Pierik [1,*], Urban Axelsson [2], Emil Eriksson [2], Daniel Salomonsson [2], Pavol Bauer [3] and Balazs Czech [3]**

[1] Energy research Centre of the Netherlands (ECN), Westerduinweg 3, 1755 LE Petten, The Netherlands

[2] Vattenfall AB, Power Technology, Jämtlandsgatan 99 , SE 162 87 Stockholm, Sweden; E-Mails: urban.axelsson@vattenfall.com (U.A.); Emil.Eriksson@vattenfall.com (E.E.); Daniel.Salomonsson@vattenfall.com (D.S.)

[3] Delft University of Technology, Mekelweg 4, 2628 CD Delft, The Netherlands; E-Mails: P.Bauer@tudelft.nl (P.B.); B.Czech@tudelft.nl (B.C.)

* Author to whom correspondence should be addressed; E-Mail: pierik@ecn.nl; Tel.: +31-224-564235; Fax: +31-224-568214.

*Received: 27 January 2010 / Accepted: 20 February 2010 / Published: 31 March 2010*

---

**Abstract:** EeFarm-II is used to evaluate 13 different electrical systems for a 200 MW wind farm with a 100 km connection to shore. The evaluation is based on component manufacturer data of 2009. AC systems are compared to systems with DC connections inside the wind farm and DC connection to shore. Two options have the best performance for this wind farm size and distance: the AC system and the system with a DC connection to shore. EeFarm-II is a user friendly computer program for wind farm electrical and economic evaluation. It has been built as a Simulink Library in the graphical interface of Matlab-Simulink. EeFarm-II contains models of wind turbines, generators, transformers, AC cables, inductors, nodes, splitters, PWM converters, thyristor converters, DC cables, choppers and statcoms.

**Keywords:** offshore wind farm electrical systems; offshore wind farm design; offshore wind farm economics

---

## 1. Introduction

Europe's offshore wind potential is enormous and able to power Europe seven times over. Over 100 GW of offshore wind projects are already in various stages of planning. If realized, these projects would produce 10% of the EU's electricity whilst avoiding 200 million tonnes of $CO_2$ emissions each year. [1].

A number of large wind farms in the North Sea is currently in the design stage. The layout and the components of these wind farm are chosen, based on a good estimate of the electricity production costs of different options. To estimate the production costs, the investment costs, the electrical losses and the produced electric power have to be determined. This can be realized by calculating the voltages and currents in all wind farm components.

In this paper, EeFarm-II is used to evaluate thirteen different electrical systems for a 200 MW wind farm with a 100 km connection to shore. The systems are grouped by their way of operation: constant speed, individual variable speed, cluster variable speed and park variable speed. For this evaluation a database with component manufacturer data of 2009 is used. The investment costs for the HVDC converters are from 2007.

## 2. EeFarm-II Model and Database Description

EeFarm-II 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 each wind speed bin, *i.e.*, for the complete range of operation of the wind farm. From the output power for each wind speed bin and the wind speed distribution, the annual energy losses and the annually produced energy are determined. The Levelised Production Costs (LPC), *i.e.*, the average production costs over the lifetime of the wind farm, are based on the investment cost, the produced energy and a number of economic parameters. Figure 2 gives an overview of the different steps in the calculation of the Levelised Production Costs.

EeFarm-II is programmed in Matlab-Simulink, which may seem an a bit odd choice because stepping through a wind farm power curve and calculating the output of a wind farm is not a dynamic simulation, the task for which Simulink was designed. On the other hand, Matlab-Simulink has a lot of advantages, also for these kind of steady state calculations:

- the graphical user interface and library facility, which makes setting up a new wind farm model from an existing set of component models very easy and transparent;
- the Simulink bus signal, which results in simple and error free connection of component models in the wind farm model;
- the Matlab data structure, which simplifies the transfer of component parameters to the wind farm model: complete sets of parameters are assigned by a single command.

An advantage of EeFarm-II is that it can handle AC as well as DC components, standard load flow models can only handle AC components. The core of EeFarm-II consists of steady state models of wind farm electrical components. The EeFarm-II component models reside in a Simulink model library, see Figure 1. A wind farm model is built by copying the model blocs to a Simulink model and connecting the blocks. The electrical model blocs have one input and one output, which is a Simulink bus. The content of a bus for all AC and for all DC blocks is the same, see table 1 for the AC bus. The component blocks are arranged and connected from the individual wind turbines 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 end connected to the turbine generator is input and the cable end connected to the turbine transformer is output. The signal direction also gives 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 coming from two turbines, a node block is used. Table 2 gives an overview of the components in the library of EeFarm-II.

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, due to the small voltage drops and the small voltage angle differences in a wind farm. For a detailed description of EeFarm-II, refer to [2].

The independent variable in the EeFarm calculation is the wind speed. The wind turbine power curve specified by the turbine manufacturer is used to determine the turbine electric power. Alternatively, the electric power of each individual wind turbine in the farm, calculated by a wind farm wake program (for instance the ECN program FarmFlow) can be used. The turbine generator and turbine transformer model are only required if the reactive power produced by the turbine has to be determined. The losses in these components are set to zero, since already included in the power curve.

**Figure 1**. EeFarm model library.

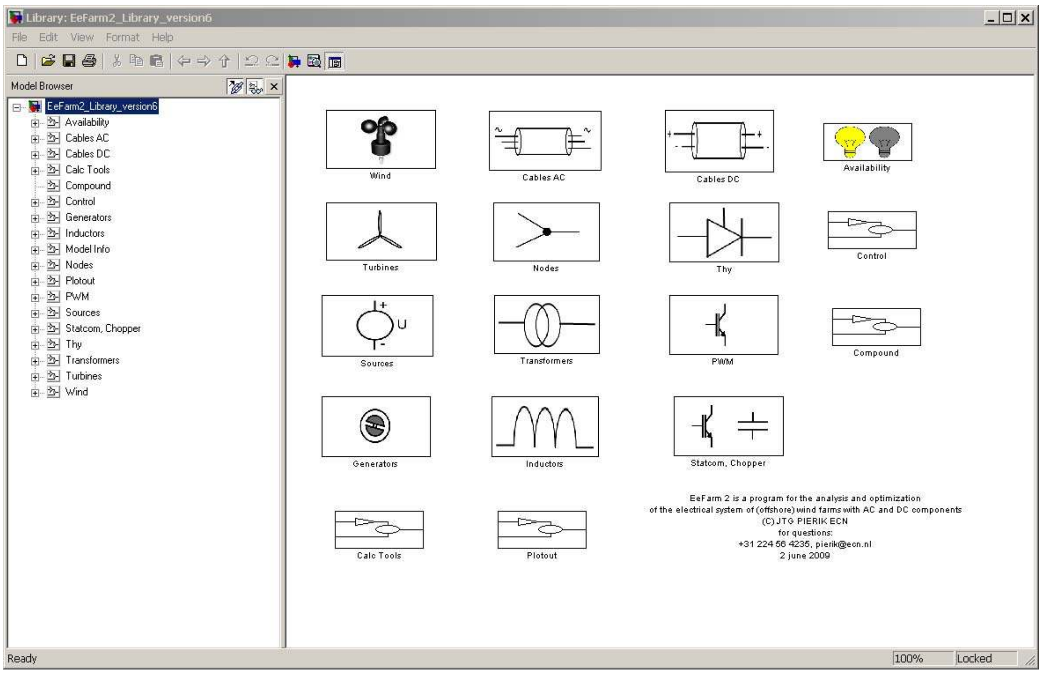


**Table 1**. AC bus signals.

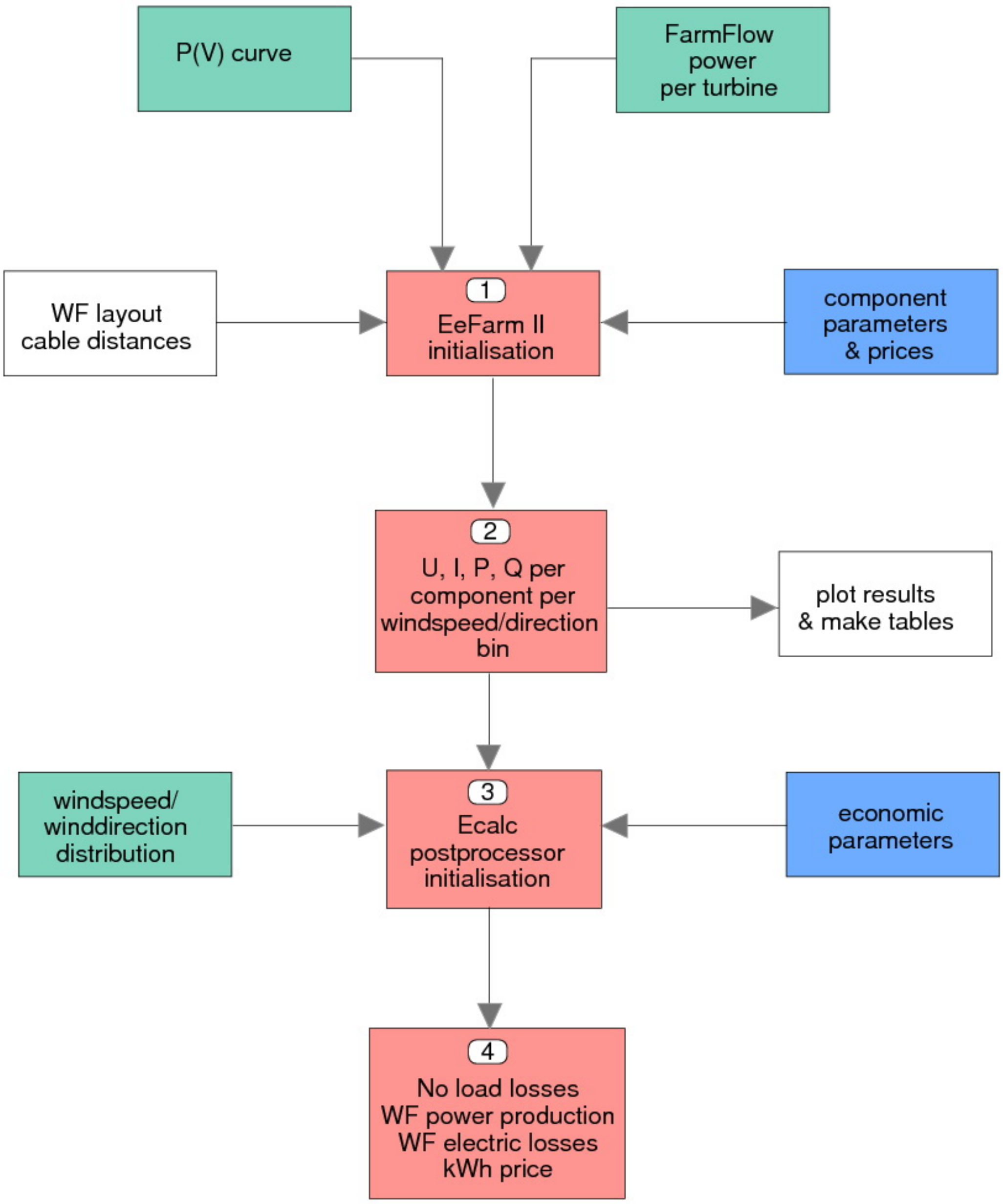
| | | |
|---|---|---|
| $U_{line,out}$ | line voltage phasor (RMS) at component output, complex number | (V) |
| $I_{phase,out}$ | current phasor (RMS) at component output, complex number | (A) |
| $P_{out}$ | power at component output | (W) |
| $Q_{out}$ | reactive power at component output | (VA) |
| $P_{in} - P_{out}$ | 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 2**. Overview of EeFarm II components.

| **Model** | **Simulink block** | **Remarks** |
|---|---|---|
| Wind | Wind | wind input block |
| | GCL wake model | Simulink implementation of GCL wind farm wake 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 $\pi$ 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, TUD, Inf | IGBT rectifier Kazmierkovski, TUD, Infineon model |
| | PWM inv Kaz, TUD, Inf | IGBT inverter Kazmierkovski, TUD, Infineon model |
| Chopper | Step-up chopper | DC-DC transformer |
| Statcom | Statcom TUD | IGBT inverter TU Delft model modified as Statcom |
| Availability | Availability | power reduction due to component failure |
| Control | Qfeedback | sets the reactive power of individual turbines |

EeFarm-II includes a database with electrical parameters (capacitance, inductance, resistance etc.) and costs of the components in wind farms. In the initialization (1 in Figure 2) a wind farm specific m-file reads the component parameters from the database and fills the component parameter structures. The component parameters are passed to the simulation 2 using a mask. This enables the use of different sets of parameters for different occurences of the same library block. The simulation calculates the voltage, current, power, reactive power, losses, not produced power due to unavailability and maintenance per component and per wind speed bin. This is input for the postprocessor 3, which determines the LPC based on the wind speed distribution and the economic parameters.

**Figure 2**. EeFarm II model overview.



## 3. Wind farm electrical system evaluation

### *3.1. Wind farm electrical system description*

The Erao-1 study [3] compared 13 electrical systems for the connection of a wind farm to the grid. Since 2001 prices and performance of some of the components have changed conciderably. Therefore, the Erao-1 systems have been re-evaluated, using the improved EeFarm program with an updated (2009) database. Figures 3–8 give the layout of the Erao-1 systems.

**Figure 3**. Constant speed systems.

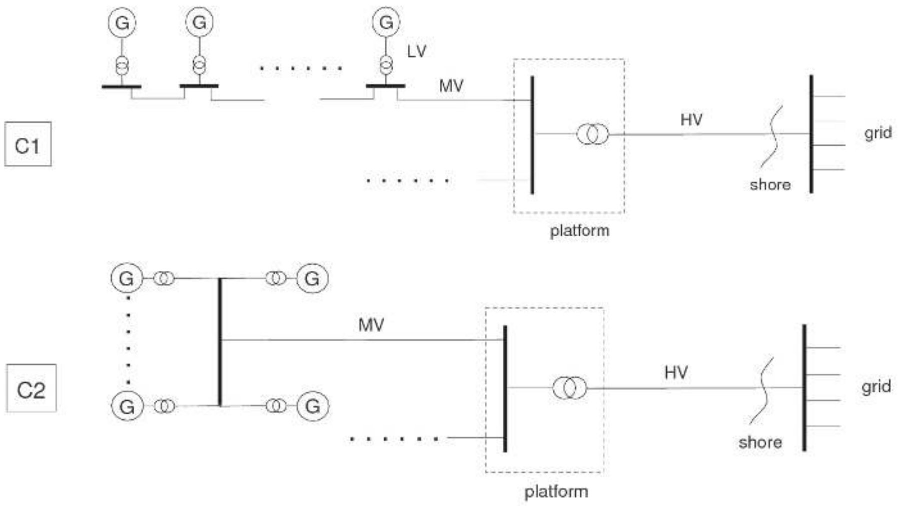



**Figure 4**. Individual variable speed with back-to-back converters.

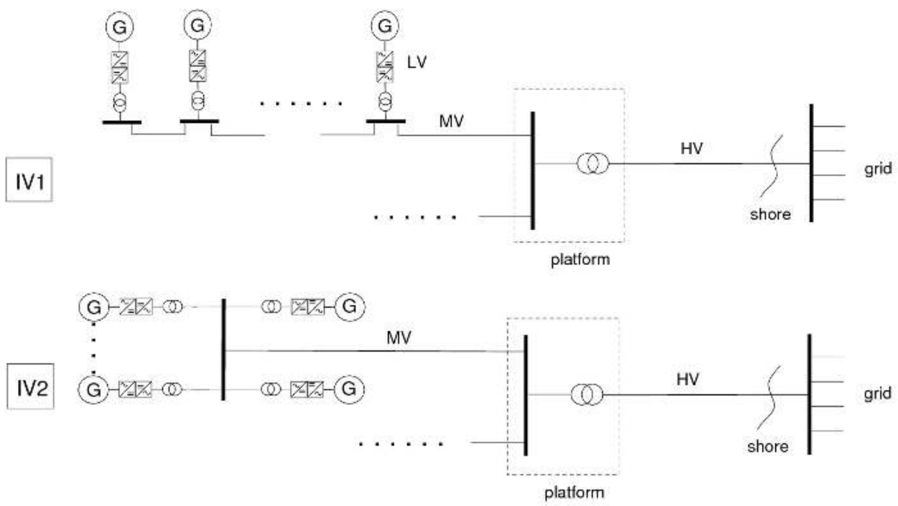


**Figure 5**. Individual variable speed with HVDC system.

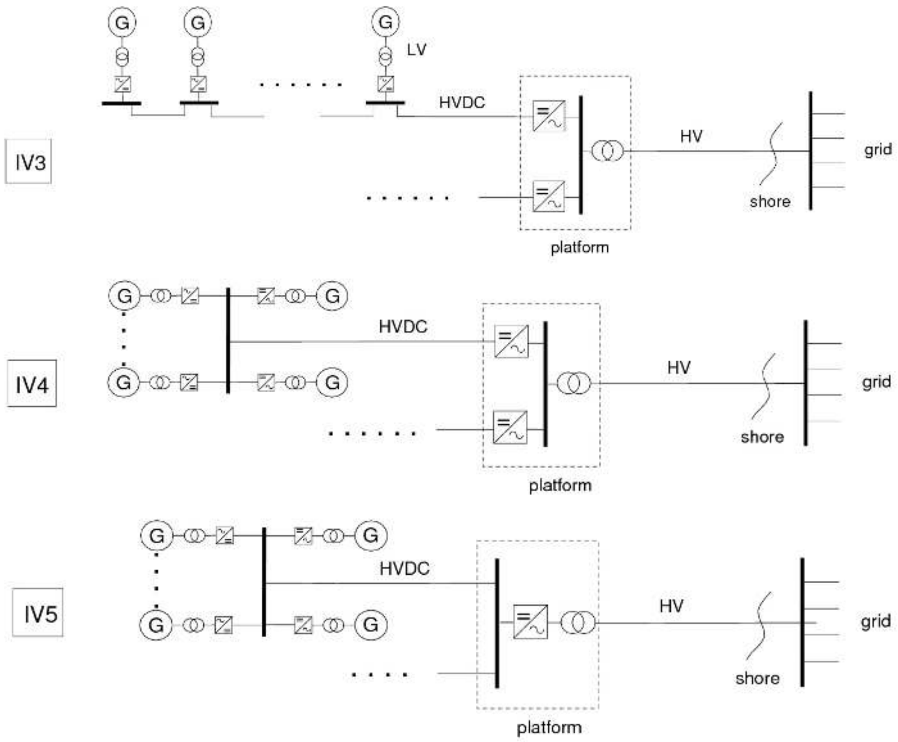



**Figure 6**. Cluster-coupled variable-speed with HVDC system.

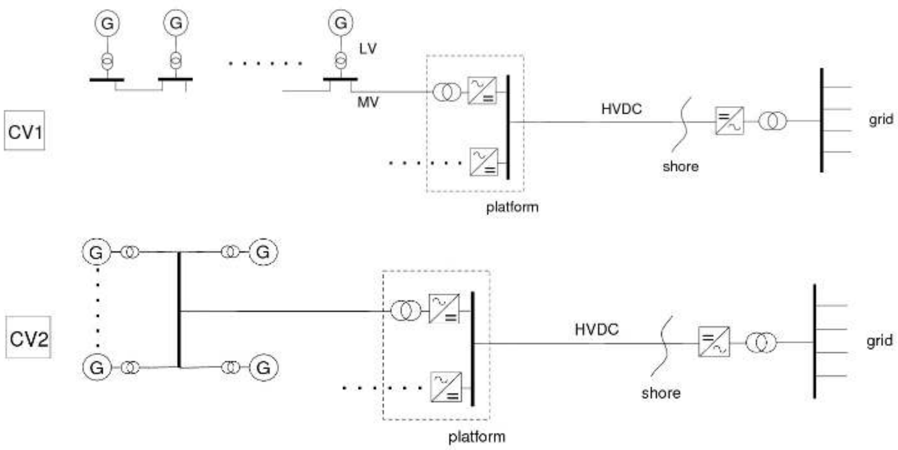


**Figure 7**. Cluster-coupled variable-speed HVDC system and step-up chopper.

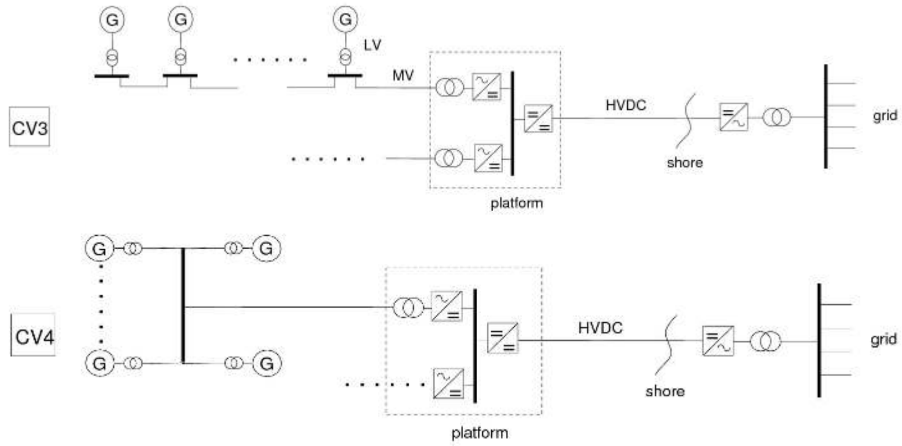
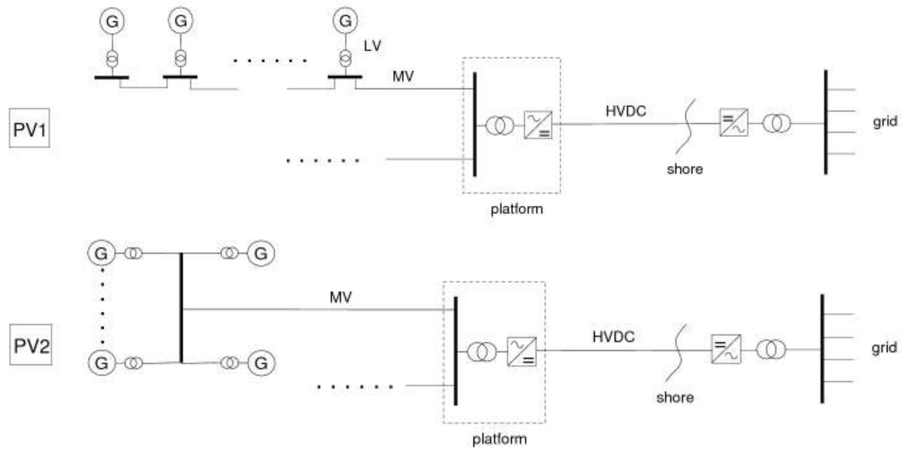



**Figure 8**. Park-coupled variable-speed system with HVDC system.




The main characteristics of the 13 wind farms are:

- a wind farm size of 200 MW;
- a wind turbine size of 5 MW;
- the length of the cable to shore is 100 km;
- two wind farm layouts: strings of five turbines (daisy chain) or stars of nine turbines connected to turbine number 10 at the center;
- four types of system operation:
  - constant speed, all AC system (C1 and C2);
  - individual variable speed with AC or DC connection to shore (IV1-IV5);
  - cluster variable speed with a number of turbines AC connected to a single rectifier (CV1-CV4);

  - park variable speed: all turbines in the farm are connected to a single AC-DC converter with a DC connection to shore (PV1 and PV2);

- in configuration CV3 and CV4 a chopper is used to increase the DC voltage of the DC connection to shore.

The wind farm size has been based on commercially available AC and DC cables and commercially available PWM converters (the smallest available 150 kV converters in the database are 100 and 200 MW). The electrical parameters and budget prices of all components have been supplied by component manufacturers in 2009 and 2007 (converters), with two exceptions: the electrical parameters and budget prices of the choppers (configurations CV3 and CV4) and of the converters with a relatively high voltage and low power rating (configurations IV3, IV4 and IV5) are based on data supplied by component manufacturers in 2001.

The economic parameters for the calculation of the levelised production cost (LPC) are:

- a wind farm life time of 12 years;
- a nominal interest rate of 7% and an inflation of 1.5%;
- the investment costs and the LPC do not include the turbine costs, only the costs of the electrical components connecting the turbines in the farm to the HV grid on land are included;
- the LPC does not include operation and maintenance costs.

Although EeFarm-II calculates the effect of component failure, redundancy and maintenance on the power production, it is not included in the following results because reliable failure data for some of the components was missing. The wind speed distribution parameters are:

- an average wind speed of 9.7 m/s;
- a Weibul factor k = 2.08.

### *3.2. Wind farm electrical system evaluation results*

Table 3 lists the electrical parameters at the PCC for maximum power of the 13 wind farms. The systems with AC connection produce reactive power at the point of connection to the HV grid. To include the effect of the decreasing capacitive current of the 100 km long AC cable, the AC cable was divided into five sections. For the all-AC systems, about half of the reactive power supplied by the 100 km long AC cable was consumed by a fixed size inductor located at the connection of the cable to the farm. The other half is consumed by the HV grid on land. The higher Q values of IV3, IV4 and IV5 are caused by a lower reactive power consumption at the farm side of the cable. These systems do not have an inductor but use partial compensation by the PWM inverter at the wind farm platform. The systems with DC connection to shore have a negative reactive power caused by the on-shore transformer. The losses for the systems with AC connection to shore are considerably less than for the DC connected systems.

**Table 3**. Electrical parameters at the connection to the HV grid at rated power of 13 electrical systems for 200 MW wind farm with a 100 km connection to shore

| | Voltage (kV) | Current (A) | Power (MW) | Reactive Power (Mvar) | Losses (MW) | Relative losses (-) |
|---|---|---|---|---|---|---|
| C1 | 133 | 902 | 189.2 | 87.3 | 10.8 | 0.0538 |
| C2 | 133 | 903 | 188.6 | 86.6 | 11.4 | 0.0570 |
| IV1 | 128 | 914 | 188.7 | 74.0 | 11.3 | 0.0566 |
| IV2 | 127 | 915 | 187.9 | 73.3 | 12.1 | 0.0604 |
| IV3 | 137 | 907 | 185.4 | 110.0 | 14.6 | 0.0730 |
| IV4 | 132 | 993 | 185.1 | 132.2 | 14.9 | 0.0743 |
| IV5 | 133 | 980 | 184.9 | 129.9 | 15.1 | 0.0755 |
| CV1 | 142 | 725 | 177.9 | –12.2 | 22.1 | 0.1106 |
| CV2 | 140 | 733 | 177.5 | –12.4 | 22.5 | 0.1125 |
| CV3 | 128 | 813 | 179.9 | –12.0 | 20.1 | 0.1007 |
| CV4 | 125 | 829 | 179.4 | –12.5 | 20.6 | 0.1031 |
| PV1 | 143 | 718 | 177.9 | –11.9 | 22.1 | 0.1104 |
| PV2 | 141 | 732 | 177.9 | –12.4 | 22.1 | 0.1105 |

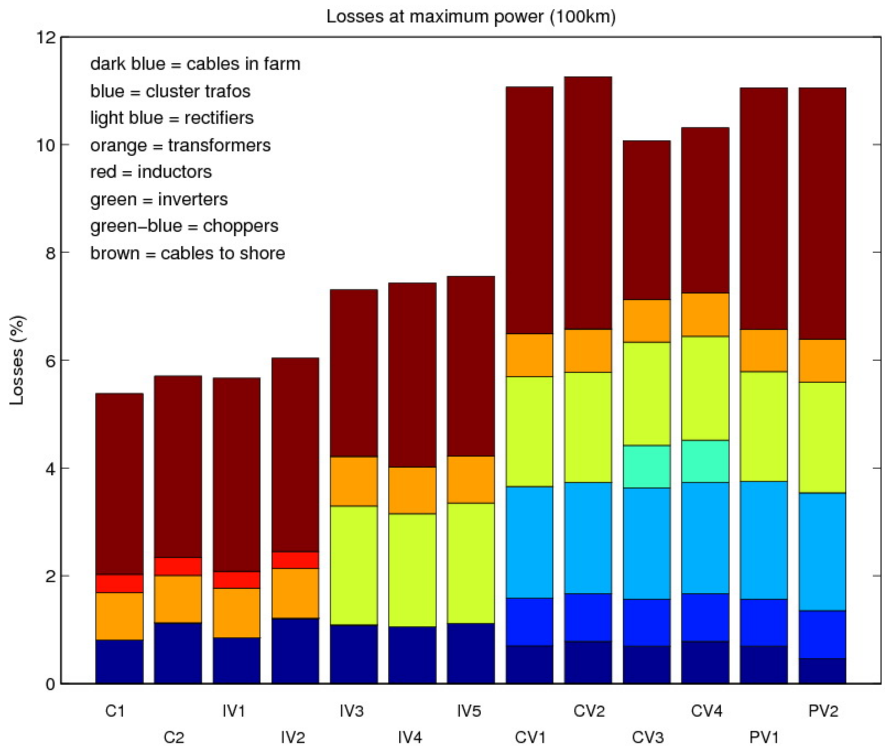
The variations in voltage of the different cases in table 3 are caused by different components and settings, especially regarding the transformers in systems with DC converters. A second reason is the choice of a constant turbine generator voltage, while the voltage drops in the farm are not corrected by an automatic tapchanger. Therefore, the voltage in some of the wind farm components is below rated. This does not have a significant effect on the losses and the energy production, however. It was checked by adding an automatic tap changer to the EeFarm-II library and comparing the results with and without automatic tapchanger for a representative system. The difference in losses at full load was only 0.5%.

Figure 9 gives the rated power losses per system component type. The cables to shore cause the largest portion of the losses. This is true for the AC as well as for the DC connected wind farms. The AC connected systems use two 138 kV three phase cables with rated apparent power of 149 MVA. The DC connected systems use a single ±80 kV, 200 MW cable. Comparing the AC and DC cable losses:

$$R_{dc} = 0.0283 \text{ Ohm/km } (100 \text{ km}, \; P_r = P_{max} = 200 \text{ MW})$$
$$P_{dc,loss} = 2 \cdot 0.0283 \cdot 1170 \cdot 1170 \cdot 100 \cdot 10^{-6} = 7.7\text{MW} \approx 4\%$$
$$R_{ac} = 0.0619 \text{ Ohm/km } (100 \text{ km}, \; P_r = 149 \text{ MVA}, \; P_{max} = 100 \text{ MW}), \; I_{max} = 451 \text{ A})$$
$$P_{ac,loss} = 2 \cdot 3 \cdot 0.0619 \cdot 451 \cdot 451 \cdot 100 \cdot 10^{-6} = 7.5\text{MW} \approx 4\%$$

Figure 9 also shows that the farm cable losses in the CV and PV systems are lower than in systems C1 and C2. C1 and PV1 use the same farm cable (30 kV, nr. 9) but PV1 has a slightly higher voltage (33 *vs.* 30 kV) and thus a lower current (86 *vs.* 95 A).

**Figure 9**. Losses at rated power divided over the system components.




The losses calculated for the PV systems are relatively high compared to the loss evaluation by Negra *et.al.* [4]. This evaluation estimated the transmission losses over the total operating range of 4–5% for HVDC VSC systems (100 km, 500 and 1000 MW). This is low compared to 8–9% for PV1 and PV2 at full load (farm cable and cluster transformer losses subtracted). For a better comparison, the relative losses over the total operating range were calculated. However, the relative overall losses are not much lower than the full load losses, see Figure 10. This is counterintuitive: one might expect that the relative losses at low power decrease due to a quadratic relation with the current, however in the AC systems, the cable current does not decrease linearly with the power due to the cable capacitive current. Therefore there is a substantial no-load loss which affects the relative losses at low power. For the DC systems a similar effect is present. The converter losses increase almost linearly with the power. Figure 11 compares the PWM converter losses estimated by the EeFarm-II models to typical manufacture data. The models give a linear relation between the relative losses (as function of the rated power). The typical manufacture data [5] is nonlinear, with a tendency to be higher at low power and lower at high power.

**Figure 10**. Losses at maximum power and cummulative over the whole range of operation.

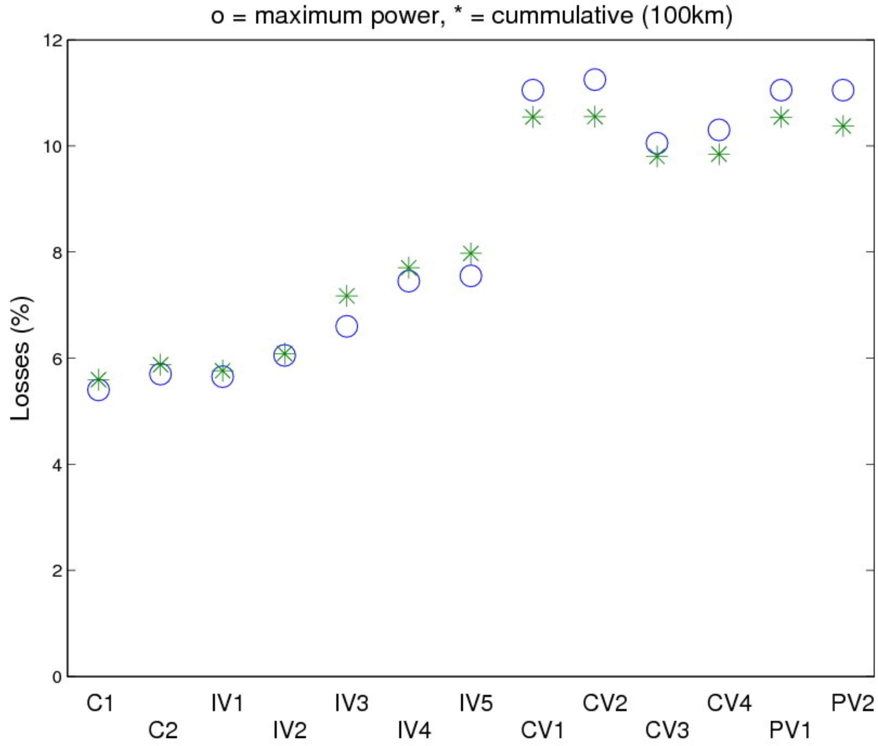



**Figure 11**. PWM converter losses (divided by the rated power): Models compared to typical manufacture data.

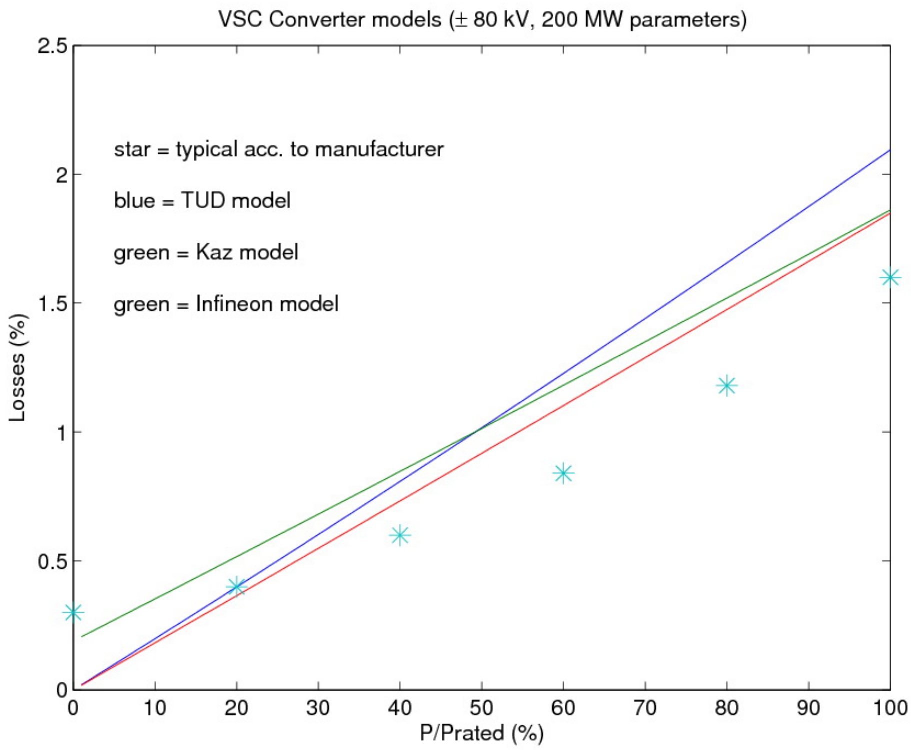


**Table 4**. Energy produced and energy losses (200 MW, 100 km).

| | Energy produced (MWh/y) | Energy losses (MWh/y) | Relative losses (-) |
|---|---|---|---|
| C1 | 938940 | 55638 | 0.0593 |
| C2 | 936141 | 58437 | 0.0624 |
| IV1 | 937275 | 57303 | 0.0611 |
| IV2 | 934051 | 60527 | 0.0648 |
| IV3 | 916412 | 78171 | 0.0853 |
| IV4 | 917979 | 76611 | 0.0835 |
| IV5 | 915285 | 79299 | 0.0866 |
| CV1 | 889662 | 104875 | 0.1179 |
| CV2 | 889597 | 104944 | 0.1180 |
| CV3 | 897070 | 97480 | 0.1087 |
| CV4 | 896641 | 97913 | 0.1092 |
| PV1 | 889702 | 104835 | 0.1178 |
| PV2 | 891353 | 103189 | 0.1158 |

**Table 5**. Investment and LPC (200 MW, 100 km, investment costs of turbines are not included).

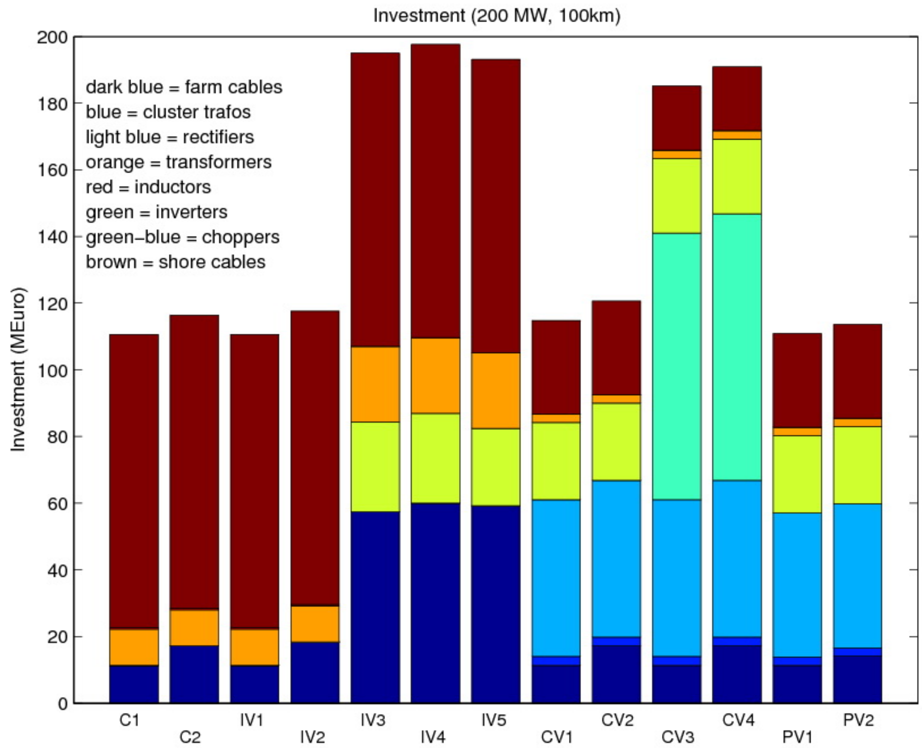
| | Investment (MEuro) | Energy produced (MWh/y) | Specific investment (MEuro/MW) | LPC (Euro/kWh) |
|---|---|---|---|---|
| C1 | 110.6 | 935227.7 | 0.5530 | 0.0137 |
| C2 | 116.4 | 932445.8 | 0.5820 | 0.0144 |
| IV1 | 110.6 | 933371.3 | 0.5530 | 0.0137 |
| IV2 | 117.6 | 930167.4 | 0.5881 | 0.0146 |
| IV3 | 195.0 | 915328.5 | 0.9751 | 0.0246 |
| IV4 | 197.6 | 917680.2 | 0.9881 | 0.0249 |
| IV5 | 193.1 | 913794.9 | 0.9655 | 0.0244 |
| CV1 | 114.8 | 884801.7 | 0.5742 | 0.0150 |
| CV2 | 120.6 | 886043.7 | 0.6031 | 0.0157 |
| CV3 | 185.1 | 892104.8 | 0.9256 | 0.0240 |
| CV4 | 190.9 | 892962.7 | 0.9546 | 0.0247 |
| PV1 | 110.9 | 884866.5 | 0.5544 | 0.0145 |
| PV2 | 113.6 | 887782.1 | 0.5680 | 0.0148 |

A reason for the high DC losses can be found in a much lower DC cable resistance: 0.0283 Ω *vs.* 0.01–0.014 Ω in [4]. A second reason can be the relatively low DC cable voltage (±80 kV). The voltage or current was not specified in Table 9 and 10 of [4], but Table 7 gives 1.68 kA, 300 kV for the 500 MW system.

Table 5 lists the investment costs of the 13 wind farm electrical systems, the produced energy and the Levelised Production Costs (turbine investment not included). The investment costs per component type are plotted in Figure 12. For the AC connected systems the most expensive component is the cable to shore, for the DC connected systems it is the rectifier, the inverter and especially the chopper, if present.

The rectifiers appear to be more expensive than the inverters. This is caused by the platform costs, which are included in the rectifier costs.

**Figure 12**. Investment costs (200 MW, 100 km).




## 4. Conclusions and recommendations

- The user friendly EeFarm-II program for wind farm electrical and economic evaluations has been described and demonstrated by comparing thirteen different electrical systems for a 200 MW wind farm at 100 km from shore;
- For this wind farm size and distance, two options have the best performance, expressed as costs of one kWh averaged over the lifetime of the wind farm: the AC system and the system with a DC connection to shore;
- The losses of the DC systems are considerably higher than for the AC systems. The losses in the DC cables to shore can be decreased considerably however by increasing the voltage, which was relatively low (±80 kV). For long AC cables increasing the voltage is problematic due to the increasing capacitive current;
- Only losses and costs have been considered in this evaluation. Systems with PWM converters do have a number of advantages which have not been taken into account, for example better controllability and reactive power production or consumption. Therefore it is recommended to develop a method to take more aspects, positive as well as negative, into account in future wind farm electrical system evaluations.

**Acknowledgements**

The EeFarm-II project has been financially supported by (a) the BSIK Program, executed by the we@sea consortium, by (b) Vattenfall Research and Development AB and by (c) the ECN Programmafinanciering of the Ministry of Economic Affairs of the Netherlands.

**References**

1. Fichaux, N.; Wilkes, J. *Oceans of Opportunity Harnessing Europe Largest Domestic Energy Resource*; European Wind Energy Association: Brussels, Belgium, September 2009.
2. Pierik, J.T.G.; Axelsson, U.; Eriksson, E.; Salomonsson, D. EeFarm II: Description, testing and application. *ECN* **2009**, ECN-E-09-051.
3. Pierik, J.T.G.; Damen, M.E.C.; Bauer, P.; de Haan, S.W.H. Electrical and control aspects of offshore wind farms. Phase 1: Steady state electrical design, power performance and economic modeling. Volume 1: Project results. *ECN* **2001**, ECN-CX-01-083.
4. Barberis Negra, N.; Todorovic J.; Ackermann T. Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms. *Electr. Power Syst. Res.* **2006**, *76*, 916-927.
5. Axelsson, U. Losses for a typical VSC converter. Personal communication, November 2008.