EERA DTOC base and near future scenario:

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SUMMARY

This report describes the definition of the first scenarios which will be calculated to demonstrate the value of the EERA-DTOC tool. Thereto it should be realized that the value of the EERA-DTOC tool could best be demonstrated by a comparison with measurements but the intended clusters for which the tool is developed are still mainly in the planning phase by which measurements to validate the tool are lacking. However, by the calculation of likely scenarios, the industrial usefulness of the tool can still be tested where moreover an 'expert view' on the results will be carried out in order to check their degree of reality.

The scenarios as described in this document are denoted as the 'base and the near future scenario', i.e. scenarios which are still relatively close to the present state of the art wind farm (clusters). This is in particular true for the base scenario which is described as a scenario which reflects 'the current way of thinking'. The near future scenario goes beyond the current way of thinking by using upscaled turbines.

The base scenario considers a 500MW wind farm which consists of hundred turbines with a rated power of 5 MW at the location where the Race Bank wind farm is planned under the UK Round 2. This farm is planned 27 km from the North Norfolk coast at the Eastern part of England. The Race Bank farm is surrounded by several other wind farms which are either operational or under construction. The turbine which is selected for this farm is the reference turbine from the former EU project Upwind, since this turbine is described in detail in public literature and reflects the current state of the art wind turbine technology.

The near future scenario assumes a 1 GW wind farm and is located at the Dogger Bank in the North Sea. It consists of 100 turbines with a rated power of 10 MW. Although 10 MW turbines are not on the market yet the INNWIND.EU reference wind turbine has been selected since a full description of this turbine is available.

The scenarios will not only be calculated by the research groups but also by the industrial users which all have their different wishes on tests to be carried out on the tool. As such it is not feasible to report a detailed road map with a precise description of every calculation to be performed, but instead the starting point and the most important input data for the calculations is given, with suggestions for calculations around this starting point in order to meet the requirements and stories as defined by end users of the tool. As such it acts as a time saver for the users where it also provides a common basis for comparison of results but still leaving sufficient freedom to each user to calculate test cases in agreement with his/her wishes.

Some near future scenario calculations have already been performed by the ECN wake and electrical models even before the EERA DTOC tool is finished. These calculations made it possible to test the description of the scenarios where moreover some interesting results on the LCOE for different distances between the turbines were obtained.

The near future scenario will eventually form the basis for the far future scenario in which unconventional options like floating turbine are considered. The far future scenario will be reported separately.

1 INTRODUCTION

1.1 Background

In WP5.3 of the EERA-DTOC project the integrated offshore wind farm design tool as delivered from WP4 [2] is demonstrated for and by the industry on the basis of likely scenarios. The scenarios as described in this document are denoted as the 'base and the near future scenario', i.e. scenarios which are still relatively close to the present state of the art wind farm (clusters). This is in particular true for the base scenario which is described as a scenario which reflects 'the current way of thinking'. The near future scenario goes beyond the current way of thinking by using upscaled turbines.

Requirements in the scenario definition are that industry itself plays an important role in them. Thereto industry has defined user stories [12] which complemented with the information from the present document forms the description of the scenarios. Thereto the present report gives the input for the scenarios together with suggestions for calculations to be carried out.

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1.2 Goal of scenarios and document

It is important to realize that validation of the integrated design tool by means of measurements is still difficult to do on the scale of clusters because large wind farm clusters are in planning rather than in operation. Nevertheless the demonstration of the EERA-DTOC tool by means of likely scenarios enables a check on the industrial usefulness of the tool on basis of the user requirements as defined in the start-up phase of the project and reported in D4.1 [12]. More specifically it should be shown that the tool is useful, easy to use, complete and robust. Moreover the 'steepness' of the learning curve will be determined and it will be checked which tutorials would have be added (e.g. simple case, videos?). Although a comparison with measurements cannot be made an expert view is carried out on the results in order to assess their degree of reality.

An important requirement for the scenario calculation is that all EERA-DTOC main modules (i.e. the wind module, the wake module, the grid module, the energy yield module and the cost module) are activated.

The present document should then be seen as a starting point and it describes the most important input data for the calculations and it gives suggestions for variations around this starting point in order to meet the user requirements and user stories. The input data in this document refer to the turbines, the location of the farms and the corresponding wind climate and the design of the electrical infrastructure. As such the goal of this document is to act as a time saver for users where it also provides a common basis for comparison of results but still leaving sufficient freedom to each user to calculate test cases in agreement with his/her wishes
By using all the information from this document the requirement to activate each module in the tool is fulfilled. The wind climate data are used in the meso-scale modelling, the turbine data and the lay-out of the farm are used in the microscale wake modeling where the lay-out and the electrical infrastructure data are used in the grid modeling. This eventually leads to an energy yield production of the farm and cost estimates.

The user stories are summarized in [12] and they showed a strong interest into cluster design requirements and the determination of the optimum spacing and positions of turbines within a wind farm including the optimization of cable layout (i.e. determining optimum cable layout, electrical configuration and number of substations). It is believed that most of the user stories can be covered with the base and near future scenario but the cluster design requirements will mainly be covered in the far future scenario description which is reported separately.

1.3 Approach

As explained in section 1.1. the present report describes the so-called base and near future scenario.

Base Scenario

The base scenario is connected to the planned Race Bank wind farm at the Eastern coast of England, see http://www.4coffshore.com/windfarms/race-bank-united-kingdom-uk18.html and https://mapsengine.google.com/map/edit?hl=nl&mid=zBjDdqwq1tDE.kInbPPDGvF7U which shows this farm to be scheduled 27 km from the North Norfolk coast. The planned capacity is 580 MW realized though 94-116 turbines in the range of 5-6.15 MW. Since the turbine type is not decided yet and because the eventual turbine data will anyhow be confidential the present scenario assumes the farm to consist of 100 UPWIND 5MW reference turbine since the UPWIND turbine is well documented in the public domain. The Race Bank wind farm is surrounded by several other wind farms which are either in operation already or they are in the planning phase. These surrounding farms are included in the scenario description.

Near future scenario

The near future scenario is connected to (aspects of) the plans for an off-shore cluster at Dogger Bank. It starts with a 1GW wind farm consisting of 100 turbines with a rated power of 10 MW using the well documented INNWIND.EU reference turbine. The farm is assumed to be located at the southern part of the Doggersbank area and it is surrounded by other wind farms similar to the planned situation for Doggersbank of figure 3.

An example for calculations to be carried out with these data forms the study performed by ECN see section 3. The study used the input for the single wind farm from the near future scenario as described in this document. In the study the distance between turbines is varied and the influence on wake losses, electrical losses and costs for electrical infrastructure is investigated. Finding the optimal distance is an important user story for wind farm developers [12]

Note that the near future scenario forms the basis for the far future scenario which will be defined separately and which will consist of large clusters (up to 10 GW) where some of the farms in the cluster are differently sized and contain floating turbines. Such far future scenario includes several grid planning options, both for the export to the mainland as for interconnecting wind farms in the cluster. It may even include interconnections with other development zones or even to other countries, combining wind power export and cross-border electricity trade.

2 SCENARIO DESCRIPTION

2.1 Wind farm lay-out and electrical infrastructure

This section presents the single wind farm lay-out and some of its characteristics. Thereto the internal layout, the intra-array design and the capability of providing ancillary services with the wind farm are briefly presented with specific suggestions for scenarios to be calculated. Note that some of the information is applicable for both the base as well as the near future scenario although the turbine types and locations of the farms are different for both scenarios.

a. Wind turbines location

The suggested layout of the farms is given in Figure 1. It is based on the layout of the Horns Rev wind farm the only difference lies in the fact that Horns-Rev considers 10x8 wind farms where the present wind farm lay-out has been modified to 10x10 wind turbines. One main 'wind farm line' is oriented in the East-West direction and the other main wind farm line slightly skewed compared to the North-South direction. In figure 1 the direction of the main wind farm lines is 5.1 rotor diameters but scenarios will be considered with different distances between the turbines. The study reported in section 3 assumes distances between the turbines ranging from 3.65 to 10 rotor diameters.

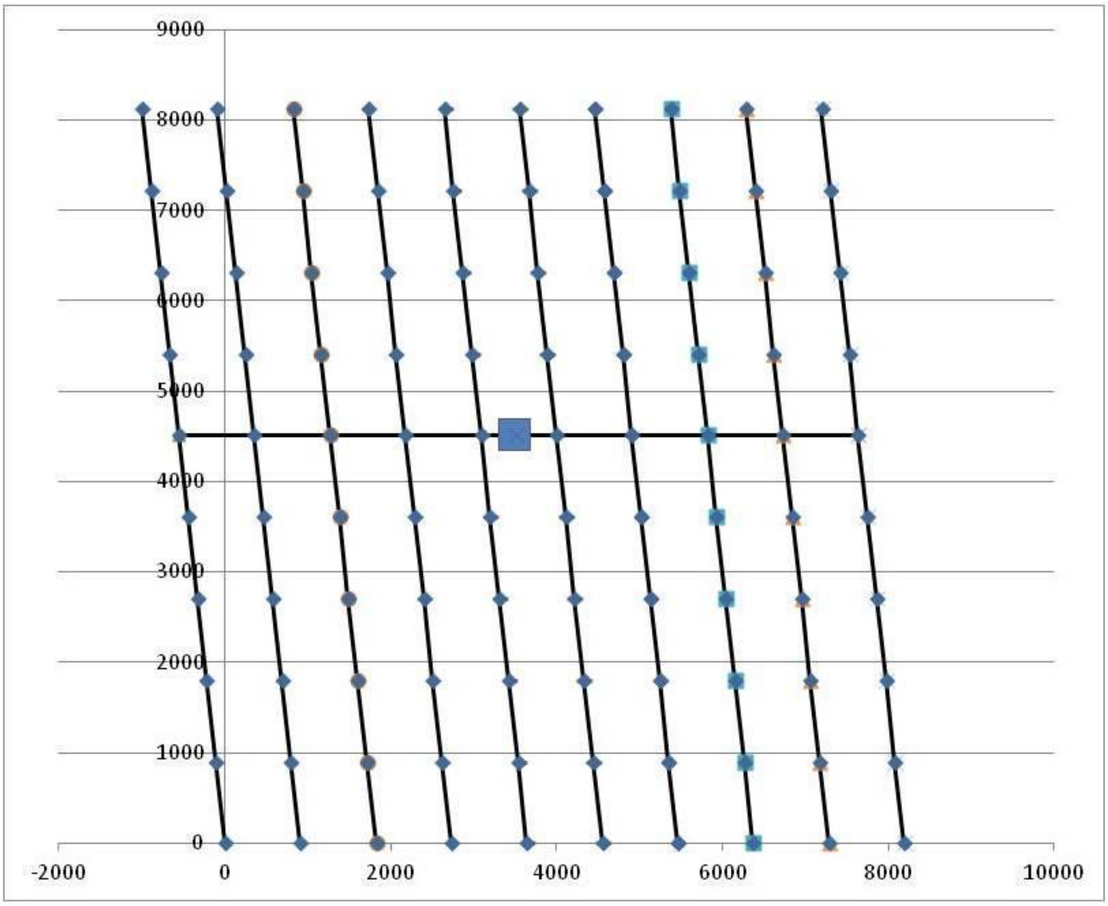

Figure 1. Layout of wind farm with the lay-out of electrical cables and transformers. In this case the distance between the turbines is 5.1D but different distances can be used.

b. Grid optimization

Part of the optimisation scenario could consist of investigating several basic intra-array infrastructures for which suggestions are given in figure 2. In the wind farm medium voltage 66 kV AC cables could be used[1] in a radial or double-sided ring topology. Some other intra-array voltages are also possible, as 33 kV AC, The optimization procedure in EERA-DTOC assumes that the location of the turbines is given beforehand.

Note that the FARMFLOW-EEFARM study from section 3 is done with the topology of figure 1, i.e. a radial topology. The cable voltage of 69kV AC.

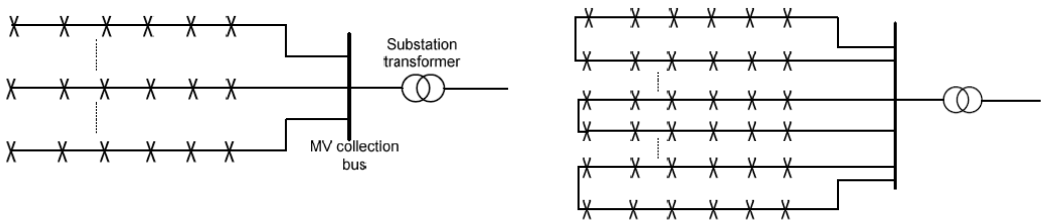

Figure 2. Possible electrical infrastructure schemas.
Left: for radial wind farm topology; right: for double-sided ring wind farm layout [3]

The intra-array will be connected to an offshore substation outside or inside the farm, from which a HVDC-VSC branch goes towards the onshore HVDC and then to an existing HVAC infrastructure. Multiple voltage possibilities could be analyzed in the optimization process: 110 kV, 132 kV, 150kV, 220 and 275 kV for AC lines and 150 kV and 300 kV for DC lines.

c. Ancillary Services provision analysis

Following the grid optimization, the analysis of the availability of power plant system services of a cluster is performed. This analysis includes the provision of:

- Frequency Support Services:
- Frequency Restoration Reserve (FRR) [4] available up-/downward regulation of the wind farms based on forecasts.
- Replacement Reserve (RR) [4] available up-/downward regulation of the wind farms based on forecasts.
- Voltage Support Services:
- Steady-State Voltage Control[2] by providing reactive current: voltage support by coordinated provision of reactive power at POI.

Also three further analyses are performed:

- Congestion Analysis, including:
  - detection: the electrical components overload for lines, transformers, inverters and all relevant electrical equipment is analyzed to detect possible congestions;
  - management[3] implementing WF capabilities: control strategies to avoid detected congestions by controlling the wind farms in a cluster.

[1] According to the recommendations presented in (Ferguson, de Villiers, Fitzgerald, & Matthiessen, 2012)
[2] This service includes the coordinated voltage control perform by Clusters at POI.
[3] Management of congestion based on HVDC inverters setpoint management is not implemented.

- Provision of Balancing Power: calculation of available/ required balancing power during intraday operation.
- Losses calculation: provided by component and summarizing the overall electrical losses.

Due to the different denominations and rules for providing the so-called secondary and tertiary reserve in different parts of Europe, the *ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators [4]* and *Operational Reserve Ad Hoc Team Report Final Version [4]* rules and definitions have been adopted in order to homogenize the approach, calculations and naming rules.

2.2 Wind Turbine Choice

Base scenario

The wind turbines from the base scenario have a rated power of 5 MW. A full description of the selected turbine is available from the former EU FP6 project Upwind [21]. If needed, the resulting power and C_{DAx} curves as calculated from this description could be obtained from ECN.

- Rated power: 5 MW
- Rotor diameter: 126 m
- Hub height: 90 m
- Wind class: IEC class Ib
- Regulation: Variable speed, collective pitch
- Orientation of rotor: Upwind, overhang 5 meter
- Rated wind speed 11.4 m/s
- Cut-out wind speed 25 m/s
- Maximum rotor speed: 12.1 rpm (maximum tip speed: 80 m/s)

Near future scenario

For the near future scenario a 10 MW turbine is selected. Such turbines are not on the market yet. Therefore the INNWIND.EU reference turbine is proposed since the data of this turbine are already made publicly available by DTU. The main characteristics of this turbine are:

- Rated power: 10 MW
- Rotor diameter: 178.3 m
- Hub height: 119 m
- Wind class: IEC class Ia
- Regulation: Variable speed, collective pitch
- Orientation of rotor: Upwind, overhang 7.1 meter
- Cut in wind speed: 4 m/s
- Rated wind speed 11.4 m/s
- Cut-out wind speed 25 m/s
- Minimum rotor speed 6 rpm

- Maximum rotor speed: 9.6 rpm (maximum tip speed: 90 m/s)
- Gearbox: Medium speed, Multiple stage generator

A detailed description on the turbine including a power curve and C_{Dax} curve as needed in many wake models can be found at: http://dtu-10mw-rwt.vindenergi.dtu.dk/

From the electrical point of view, for the purpose of AC grid stability simulations, wind turbine models are described by wind conversion technology according to the new IEC standard, the IEC 61400-27-1[4], in four categories: type 1, 2, 3 and 4, were types 3 and 4 are the most relevant including (DFIG, SCIG, WRSG and PMSG). Technical capabilities are presented to analyze the possible available Ancillary Services provided by wind turbines, e.g. reactive power provision capabilities. Note that for the present purpose, the electrical design of the turbine can be considered independent of the aerodynamic design as long as the correct tip speed ratios (and the resulting rotor characteristics) are obtained.

2.3 Development Area Location and Description

Base scenario

The location of the farm of the base scenario is at the planned Race Bank wind farm at the Eastern coast of England, see http://www.4coffshore.com/windfarms/race-bank-united-kingdom-uk18.html and https://mapsengine.google.com/map/edit?hl=nl&mid=zBjDdqwq1tDE.kInbPPDGvF7U which shows this farm to be planned 27 km from the North Norfolk coast. The water depths are between 6 and 23 m.

The farm is surrounded by several neighbouring farms. These are:

- Lincs 270 MW wind farm consisting of 75 Siemens SWT 3.6 120 turbines at a distance of 25.5 km and 246.5 degrees from Race Banks
- Linn and Inner Dowsing 97,2 MW wind farm, consisting of 27 SWT 3.6 107 turbines at a distance of 31.21 km and 238.364 degrees from Race Banks
- Triton Knoll 200-300 MW wind farm consisting of turbines in the range from 3.6 to 8 MW (unknown yet since the farm is still in the planning phase)..It is suggested to apply 50 turbines of 5 MW (i.e the NREL RWT). The farm is located approximately 18.2 km and 165.815 degrees from Race Banks .
- Sheringham Shoal 316.8 MW farm consisting of 88 Siemens SWT 3.6 107 turbines at a distance of 26.693 km and 131.259 deg, from Race Banks
- Dudgeon 360-400 MW wind farm consisting of Siemens SWT 6.0 154 turbines at a distance of 37.259 km and 94.242 deg from Race Banks (in planning phase)

More information on these farms can be found from http://www.4coffshore.com/windfarms/

Near Future Scenario

The near future farm is located at the Dogger Bank East of North England in relatively shallow waters (18 to 63 meters), see figure 3. Dogger Bank is part of the UK Crown Estate Round 3 area (8,660 km^2, the largest of the Round 3 zones) with distances between 125 and 290 kilometers off the east coast of Yorkshire, UK.

The development consortium Forewind has defined several projects, each divided in phases of 1.2 MW: Creyke Beck A and B, Teesside A and B (where Teesside C and D are planned for a later stage). The whole estimated capacity of Dogger Bank could add up to 9GW,

Figure 3 shows approximate locations of Creyke Beck A and B and Teesside A and B projects. The 1GW wind farm under consideration is then suggested to be located at the Creyke Beck A site, which is the most Southerly project from figure 3, 131 km from the shore at its closest point. The surrounding farms are given by the above mentioned projects: Creyke Beck B is located in North from the Creyke Beck A site, also 131 km from the shore at its closest point. Teesside A is furthest away from the shore with a closest point from shore at 196km and Teesside B is 165 km from shore. These farms could be assumed to have a 1GW capacity as well with a similar layout as suggested for the Creyke Beck A farm.

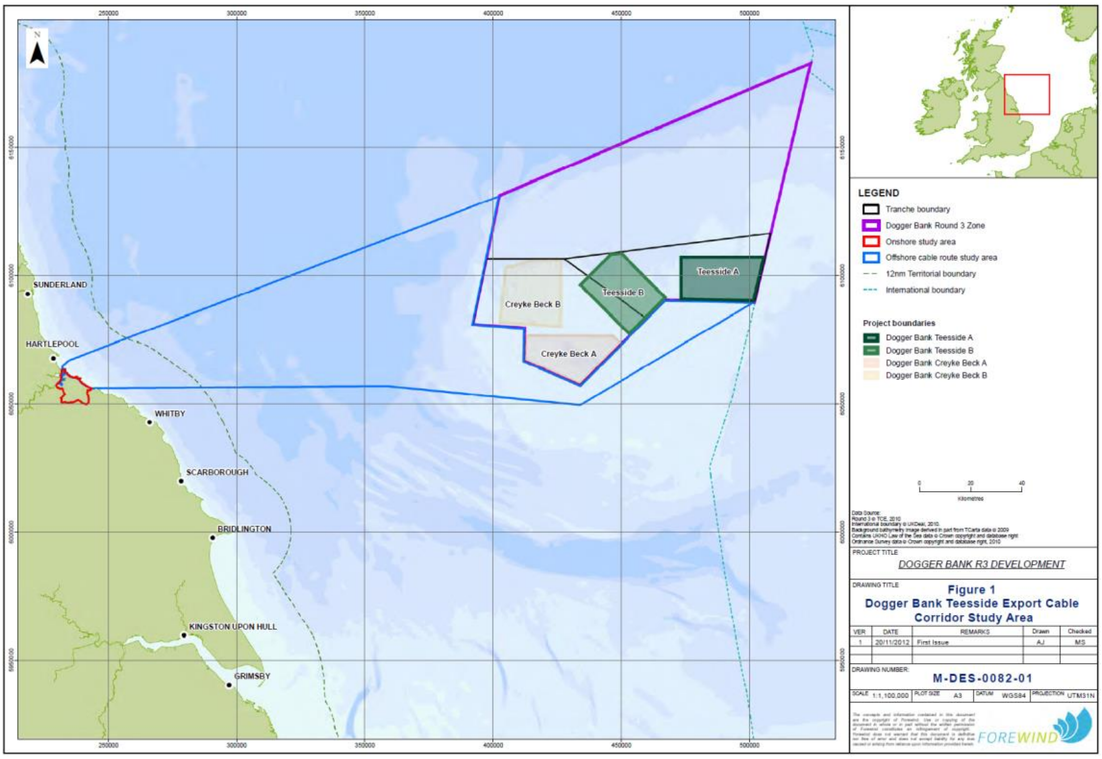

Figure 3. Location of Dogger Bank projects [9].

2.4 Available Meteorological and Reanalysis Data

Wind data for the base scenario i.e. at the Race Bank location can be retrieved from http://www.4coffshore.com/windfarms/race-bank-united-kingdom-uk18.html

The wind power meteorology of the Northern European Seas recently has been studied in the EU-Norsewind project www.norsewind.eu based on an array of wind profiling LIDaR, satellite data and mesoscale modelling. The results are available at the web site. Furthermore, in depth studies by KVT on the wind climate can be useful for the scenarios. Note that the first calculations from section 3 are performed with a constant wind climate over the farm.

Data provided by CorWind model is used to create long-term correlated time series used during the variability and predictability analysis and the optimization of the grid layout.

2.5 Grid Optimization and Constraints

The optimization of the grid layout in EERA-DTOC is implemented by three models: the EEFARM model which is in particular used for intra array optimization (for the definition of intra array design reference is made to the Glossary). A description of EEFARM is given in [18]. It basically determines the losses within the electrical infrastructure of a farm, the losses due to electrical component failures and the costs of the electrical infrastructure. The inter array aspects are mainly covered by the NET-OP [13] model and a simulation tool based on WCMS. Given the location of the wind farms and the onshore nodes, the optimization process creates a basic layout clustering the wind farms and defining the best suitable technology of the branches (AC/DC) and their capacities. Restrictions and already existing or planed lines can be defined as constraints. The main constrains for the electrical development and grid optimization perform by EERA-DTOC are those already announced by the developer: *"Forewind is now proceeding with the development of a total of 6 GW of offshore wind farm generation capacity [...]. From a technical perspective, work has begun to design the electrical system to connect from the offshore zone back to the National Grid substations. These connections will make use of innovative High Voltage Direct Current (HVDC) technology."*[5].

[5] http://www.forewind.co.uk/zone-development/grid.html

3 PRELIMINARY SCENARIO SIMULATION AND ANALYSIS FROM ECN

This chapter summarizes the procedure, inputs and outputs of some first calculations carried out by ECN using the aerodynamic tool FarmFlow and the electrical tool EEFARM, see also [20]. It is intended to serve as inspiration for other EERA-DTOC users .

Procedure

The near future wind farm (i.e. the 1GW wind farm at the Doggersbank location) has been calculated with a combination of FarmFlow and EEFARM from ECN. Thereto the farm was first calculated with a large inter-turbine spacing of 10 rotor diameters. Under these circumstances the aerodynamic losses are expected to be limited but the electrical losses and the costs for the electrical infrastructure are high which may lead to suboptimal costs/kWh

Next the inter-turbine spacing was decreased in steps towards a very short distance of 3.85D. This was expected to increase the aerodynamic losses where at the same time the costs and losses from the electrical infrastructure are lowered. All these aspects are covered in the ECN tool which enables the determination of the optimal inter turbine spacing in terms of costs/kWh and as such demonstrating the value of a combined electrical and aerodynamic wind farm tool.

Inputs

The input depends on the modules selected in the EERA-DTOC. For example the use of CFD wake models will require more detailed inputs than the use of engineering wake models.

In the ECN calculations the following input was needed:

- Lay-out of turbines in the farm, see figure 1
- Rotor diameter, C_{Dax} curve, Power curve and hub height from section 2.2.
- An appropriate Weibull distribution and wind rose was applied with a turbulence intensity of 7% (constant all over the year) and neutral conditions. At a later stage stability effects and the distribution of turbulence intensities could be included (Charnock's effect!).

For simplicity of this demonstration the electrical model was limited to the collection grid, which include:

- Wind turbines, represented by their active power output at 1kV nominal voltage and a fixed reactive power setting of 0MVAr.
- Wind turbine transformers: The nominal voltage of the turbine transformers is 1kV/69kV and the power rating is 10 MVA.
- Layout and array cables according to figure 1. The wind farm was fitted with a single cable type, which is a 3-core XLPE cable (3x240 mm^2), rated for 69 kV, 58.4 MVA.

For the calculation of the Levelized Transport Costs (LTC) within the wind farm the following economical parameters have been used:

- system life time: 12 years,
- nominal interest rate: 7%,
- inflation rate: 1.5%,
- wind farm availability: 90%,

Outputs

The main output from the FARMFLOW-EEFARM calculations were the energy production as well as the investment costs of the electrical infrastructure for different distances between the turbines in the farm, see the figures 4 and 5. These data can eventually be implemented into an overall LCOE model as currently under development at ECN. Note that EEFARM only considers the costs associated to the electrical infrastructure but this is considered to be the most essential cost information in order to assess the influence of different distances between the turbines (note that the costs for use of land/sea can be included relatively straightforward). The most interesting information from these results is the linear increase of investment costs with distance where the increase in energy yield levels off with distance. As such the increase in energy yield will eventually not compensate the increase in investment costs anymore.

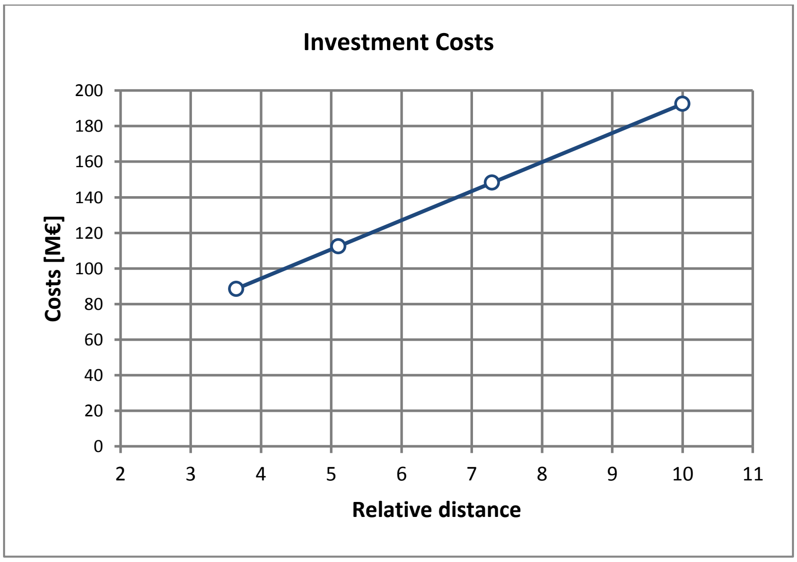

Figure 4 Investment costs as function of wind turbine spacing distance.

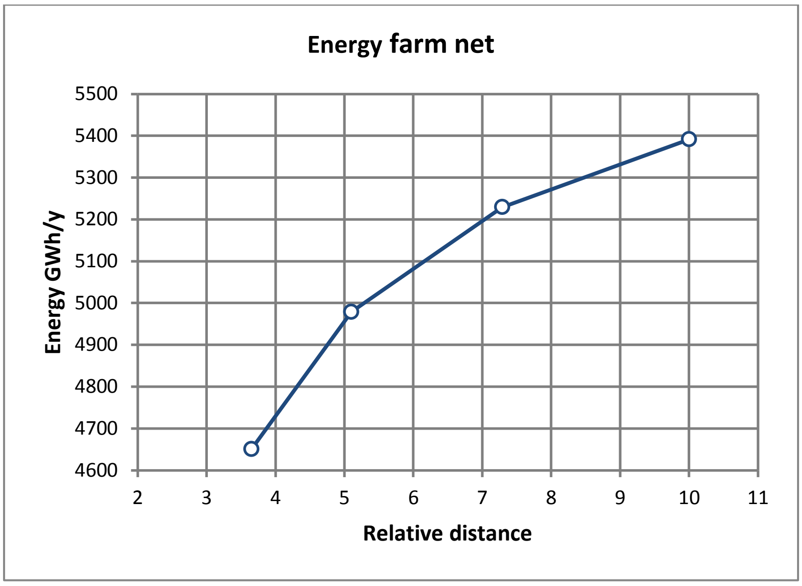

Figure 5 Net wind farm energy yield as function of wind turbine spacing distance.

Also note that several intermediate results will become available dependent on the codes used. The FARMFLOW-EEFARM tool provides the (wake) wind field at different locations in the farm (also turbulence intensities for a preliminary assessment of loads), the individual energy production of the turbines in the farm, electrical losses due to failure etc, see [21]

A suggestion for further scenario calculations is to assess the wake losses and the resulting LCOE for a different wind turbine type. It is then interesting to compare the near future scenario as described above i.e. the 1GW wind farm with the 10 MW INNWIND.EU reference turbines to a similar wind farm using 10 MW turbines with low induction rotors. The main motivation for designing wind turbines according to a low induction philosophy lies in the lower aerodynamic loads but as a side effect it will lead to lower wake effects. This makes such turbines extremely interesting to consider in EERA-DTOC. A design for a low induction turbine will become available from the EU project AVATAR http://www.eera-avatar.eu/ It is based on the INNWIND.EU reference turbine but it has been designed to have a lower induction. Consequently this turbine is expected to have a slightly lower C_P reached at a larger rotor diameter leading to a higher energy production but approximately similar aerodynamic loads (And lower wake effects). Obviously the larger diameter increases the **relative** mutual distance between the turbines is decreased which might enhance the wake effects.

4 GLOSSARY

Ancillary services: are all grid support services required by the transmission or distribution system operator (TSO/DSO) to maintain the integrity and stability of the transmission or distribution system as well as the power quality[6].

Cluster: see Wind Farm Cluster.

Intra array design: Covers the design aspects **between** the wind farm

Inter array design: Covers design aspects **within** several wind farms

LIDaR (LIght Detection and Ranging or Laser Imaging Detection and Ranging): is an optical remote sensing technology that can measure the distance to, or other properties of, targets by illuminating the target with laser light and analyzing the backscattered light.

Point of Interconnection (POI) or Point of Connection (POC): is the point at which the Wind Farm's electrical system is connected to the public electricity system.

Point of Common Coupling (PCC): is the point on the public electricity network at which other customers are, or could be, connected. Not necessarily the same location as point of connection.

Wind Farm (WF): defines the aggregation of a number of WTs connected to the same substation (or collector system station), and controlled by only one autonomous WFC. WF have one only POI and one WFC.

Wind Power Plant (WPP): set of independent WF controlled by a unique WFC which operates and manages the entire set of WF as a power plant. A WPP could implement one or more than one POI but only one WFC.

Wind Farm Cluster (Cluster): set of independent WF/WPP controlled by their own WFC that are jointly managed by an special control system operating each single WF/ WPP in a coordinated manner through their own WFC. The pooling of several large wind farms to clusters up to the GW range facilitates the integration of large amounts of variable generation into electricity supply systems. Cluster management includes the aggregation of geographically dispersed wind farms according to various criteria, for the purpose of an optimized network management and optimized generation scheduling. The scope and size of a Cluster is mainly limited by the services provided, namely: in case of frequency control, the WF/WPP integrating the Cluster could be disperse and far away one from the others; providing voltage control, due to the locality of the phenomena, integrating WF/WPP must either connected to the same POI or located nearby to provide effectively the intended service.

[6] Refer to (EURELECTRIC, 2004)

5 LIST OF ACRONYMS

CFD	Computational Fluid Dynamics
DFIG	Doubled-Fed Induction Generator
DTOC	Design Tool for Offshore wind farm Clusters
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
ECN	Energieonderzoek Centrum Nederland (Energy Research Centre of the Netherlands)
EERA	European Energy Research Alliance
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FACTS	Flexible AC Transmission System
FSCG	Full Scale Converter Generator
GW	Giga Watt
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
kV	kilo Volts
KVT	Kjeller Vindteknikk AS
MW	Mega Watt
NC RfG	ENTSO-E Network Code for Requirements for Grid Connection Applicable to all Generators
O&M	Operation and Maintenance
PMSG	Permanent Magnet Synchronous Generator
SCIG	Squirrel Cage Induction Generators
SO	System Operator (indistinctly TSO or DSO)
TSO	Transmission System Operator
TYPE 3	Variable speed, double-fed asynchronous generators with rotor-side converter
TYPE 4	Variable speed generators with full converter interface
UK	United Kingdom
WP	Work Package
WRSG	Wound Rotor Synchronous Generator

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