EERA DTOC

THE EUROPEAN ENERGY RESEARCH ALLIANCE
DESIGN TOOLS FOR OFFSHORE WIND FARM CLUSTER

Report on tools and results from a case study (D2.3)

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TABLE OF CONTENTS

1 INTRODUCTION

According to projections by EWEA [1] the cumulative offshore wind power capacity in EU member states will increase from 5.3 GW in 2012 to 40.0 GW in 2020 and further to 150 GW in 2030. In terms of electricity production, this amounts to about 4.1 % of EU electricity consumption in 2020 and 13.9 % in 2030.

A large part of the offshore wind power capacity to be built out in the next years will come in the North Sea and the Baltic Sea. Many wind farms are likely to be installed in far offshore locations with related challenges regarding grid connection, both in terms of technology and costs. Moreover, increased wind power capacity increases the need for power interconnectors to balance the variable wind power output against e.g. storage hydro power in Scandinavia. It is therefore likely that combined solutions where wind farm grid connection is considered together with power interconnector planning, with power cables serving the dual goals of exporting offshore wind power and contributing to power balancing and power trade between countries or regions.

Large scale offshore wind power development far from shore also raises the question of whether clustering may be beneficial to reduce grid connection costs and possibly also environmental impact related to e.g. cable landfall and onshore grid connection infrastructure. From a society point of view, clustering appears attractive, since it enables a sharing of infrastructure [2]. In Germany, this approach has already been adopted, with offshore substations already built and planned. However, the economic benefits of clustering depend on available power capacities and space limitations. For example, two wind farms can only share power export cables if their capacities do not exceed the maximum available cable capacity. If two cables must nevertheless be used, the benefit of clustering is less obvious.

For these reasons, it is desirable to assess grid connection options for offshore wind farms in a way that considers all wind farms and interconnectors within an area at the same time, and where clustering and combined solutions including power interconnectors are included in the design process. This is indeed the approach taken by *Net-Op DTOC* which is a software tool for offshore wind farm clustering and grid connection optimisation. This tool is described in Chapter 2.

Internal wind farm collection grid design is a different type of problem. First of all, collection grid design is a matter for the wind farm developer and is of little consequence for the wider society. The relevant optimisation is therefore not socio-economic, but needs to represent the wind farm developer's objectives, e.g. maximised return on investment. Secondly, although in principle an optimisation similar to the one outlined above can be applied, the definition of the cost function and required constraints would have to include much more detail in order to capture all relevant design options. This in turn is problematic since it inevitably gives a computationally very complex and time-consuming problem, and because it would require a very large amount of input data that is not readily available, making it very difficult to use the tool in practice. For these and other reasons, the Net-Op approach is not applied to internal wind farm electrical design. A procedure for the electrical design of the internal wind farm collection grid has instead been described in a report (deliverable D2.2). This procedure provides a step-wise outline of the design process, and a discussion of the main design variables and choices that need to be made. The procedure is outlined in Chapter 3.

The aim of this report is twofold. Firstly, it will describe the design tools and procedures briefly discussed above. Secondly, in Chapter 4, it will describe a case study with an outline of the specifications, the design process using these tools and procedures, and finally an analysis of the results.

1.1 Background

This report is a result of work done within the work package on *interconnection optimisation and power plant system services* (WP2) within the EERA-DTOC project[1].

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[1] www.eera-dtoc.eu

The EERA-DTOC project is funded through the EU's Seventh Framework Programme (FP7) and runs from January 2012 to June 2015, and is coordinated by DTU Wind Energy. The project aims to develop a multidisciplinary integrated software tool for an optimised design of offshore wind farms and clusters of wind farms.

The project consists of 6 work packages in addition to project management:

- Wake modelling (WP 1)
- Interconnection optimization and power plant systems (WP 2)
- Energy yield prediction of wind farm clusters (WP 3)
- Integration and development of software (WP4)
- Experiments. Validation of the designed tool (WP 5)
- Dissemination and exploitation activities (WP 6)

The EERA-DTOC acronym is a combination of the European Energy Research Alliance (EERA), and Design Tools for Offshore Wind Farm Cluster (DTOC).

1.2 Tools and procedures

The tools and procedures described in this report are summarised in Table 1.

Table 1: Tools and procedures for electrical grid design

Name	Type	Description
Net-Op DTOC	software tool	Automated clustering and grid connection optimisation
Wind farm cable minimisation	software tool	Matlab script for minimization of collection grid total cable length
Clustering	procedure	Method for automated clustering of wind farms
Grid connection optimisation	procedure	Method for optimised offshore grid design
Collection grid design	procedure	Design procedure

2 CLUSTERING OF WIND FARMS AND GRID CONNECTION DESIGN

This chapter describes the software tool and procedures for clustering and grid connection optimisation of offshore wind farms, where each wind farm is treated as a single node. The software tool, Net-Op DTOC, which is an upgraded version of Net-Op [3], is a separate project deliverable (D2.1) and is also described in the accompanying documentation [4].

Grid connection of offshore wind farms differ from grid connection of onshore wind farms in several significant ways. Firstly, the offshore location means that power transmission has to be through subsea cables, something which adds costs and constraints. Secondly, there is in most cases no pre-existing offshore electricity grid that offshore wind farms can connect into. And thirdly, the long distances from onshore connection points for many planned connection points brings with it technological challenges, but also new possibilities regarding grid layout; when distances are large it is more relevant to consider the wind power grid connection in tandem with power trade possibilities. An obvious possibility is for the offshore grid to serve more than one purpose, exporting power from wind farms, but also allowing trade between different price areas, or indeed allowing the wind farm to trade in multiple markets.

These considerations are at the core of the Net-Op design approach. It takes into account the possibility of trade with different prices at onshore connection points, and optimises the grid from a socio-economic benefit point of view. The optimisation finds the optimal solution such that the demand is covered by the cheapest possible mode of production. The comparison between investment costs of offshore wind electrical infrastructure and the operational costs of generation for the other generation sources in the system determines the cost-beneficial production output of the offshore wind clusters.

The Net-Op tool takes a high-level perspective, avoiding technical details. It is aimed at long-term planning at a high-level, what in the project has been denoted a "strategic planner", such as government and government agencies, transmission grid operators, and for academic studies.

2.1 Approach

As discussed in the introduction (Chapter 1) the offshore wind farm clustering and grid connection design is interlinked and requires a common approach. Of course, how the offshore grid should be designed depends on where wind farm clusters or other offshore hubs are located. On the other hand, the optimal clustering also depends on the offshore grid structure.

The problem can be formulated in terms of a number of nodes representing wind farms and potential clusters and connection points, and a number of branches representing potential connections (cables and converters) between the nodes. Based on a cost function (see below), an optimisation algorithm can then determine which connections to realise, and what their power capacities should be.

Potential nodes and branches can be assigned an investment cost that depends on the distance (which in turn is computed from the location of the nodes), the power rating, and the type of node or branch, e.g. whether it is a HVAC or HVDC cable. It is reasonable to approximate this cost using a linear model where power rating and number of units are independent variables. These variables are continuous and integer variables respectively.

A linear cost function is appropriate for three reasons: it gives a reasonable approximation to the real costs; it requires a limited amount of input data; and it simplifies the computational complexity of the problem. The first point is important for the results to be trustworthy. And indeed, linear cost functions are believed to be sufficient for the coarse level of analyses that Net-Op is intended for. The second point is important for the usability of the tool: It is often a difficult task to collect realistic cost data, and the more complex the model, the more data has to be included. If this data is not available, a more detailed model is likely to add only to the uncertainty of the results. On the other hand, if detailed cost data is available, these can be used to derive the appropriate linear cost parameters before these are fed into the model. The third point is important because of limited computational power. There are well-defined algorithms for optimisations with linear and quadratic cost models, but anything more complicated gives a much more non-standard and computationally difficult problem. Since computation time is already a limitation of this type of problem, added complexity is likely to render the problem practically unsolvable.

The optimisation problem thus becomes a mixed integer linear programming (MILP) problem, with a cost function that includes the investment costs plus present day value of the cost of generation during the wind cluster lifetime. The computation time is linked to the number of integer parameters, i.e. which branches are realised (and how many copies). Since there are many ways to connect a given number of nodes, the number of possible branches easily becomes large, and the number of possible combinations of branches becomes extremely large. This is a simple combinatorial fact: with N nodes, there are $B = N(N-1)/2$ possible branches, which gives

$$C = \sum_{b=0}^{B} \binom{B}{b} = 2^B \tag{1}$$

possible combinations, if we only assume none or one cable per branch. For example, 10 nodes gives $B = 45$ and $C = 3.5 \cdot 10^{13}$, and 20 nodes gives $B = 190$ and $C = 1.6 \cdot 10^{57}$ possible combinations. In practice this means that even a modest number of nodes lead to an extremely large number of possible combinations. For reasons of computation time this means that it is infeasible to include all possible branches in the optimisation. It is therefore necessary to limit the number of branches to consider, and this is done by explicitly specifying the allowable branches (rather than including all possible ones).

This type of optimisation furthermore takes as an input the location of all nodes, including the location of potential cluster nodes. In other words, it is necessary to specify the number and coordinates of potential cluster nodes prior to the actual optimisation. In this way, wind farm clustering is determined via the optimisation only in the sense that the optimisation picks the best alternatives from a limited list of pre-defined options.

The above considerations motivate a split in the automated design process, with the initial pre-processing phase aiming to suggest cluster nodes and select allowable branches and, and the final phase specifying and solving the MILP problem.

These steps are all included in the Net-Op DTOC tool. In the following, the procedure for wind farm clustering is described in Section 2.2, the procedure for grid connection optimisation (including the selection of allowable branches) is described in Section 2.3, and the Net-Op DTOC implementation is described in Section 2.4.

2.2 Clustering of wind farms

The procedure for clustering of wind farms aims to suggest reasonable wind farm clusters that are used as input in a subsequent grid connection optimisation which determines whether the cluster should be realised or not. The following description includes some general remarks regarding clustering and the *k-means* method used, before an outline of the implemented clustering procedure is outlined in Section 2.2.3.

2.2.1 Why pre-clustering?

In principle, there is no need to explicitly pre-cluster wind farms before the grid optimisation, since this could be done as part of the optimisation itself. However, this would require all possible connections between offshore nodes (wind farms) to be included as allowable branches in the optimisation. As discussed above, this easily leads to a practically unsolvable problem.

The objective of the pre-clustering is to generate a limited number of cluster nodes and thereby a reduced number of allowable branches, which is necessary to avoid excessive computation time. The optimisation step will then pick out the best connections, and determine whether any given cluster should be realised or not, and also whether any given wind farm should be connected to the cluster or connected directly to shore.

The difference between optimisation with pre-clustering and without pre-clustering and using all possible branches instead, is illustrated in Figure 2-1.

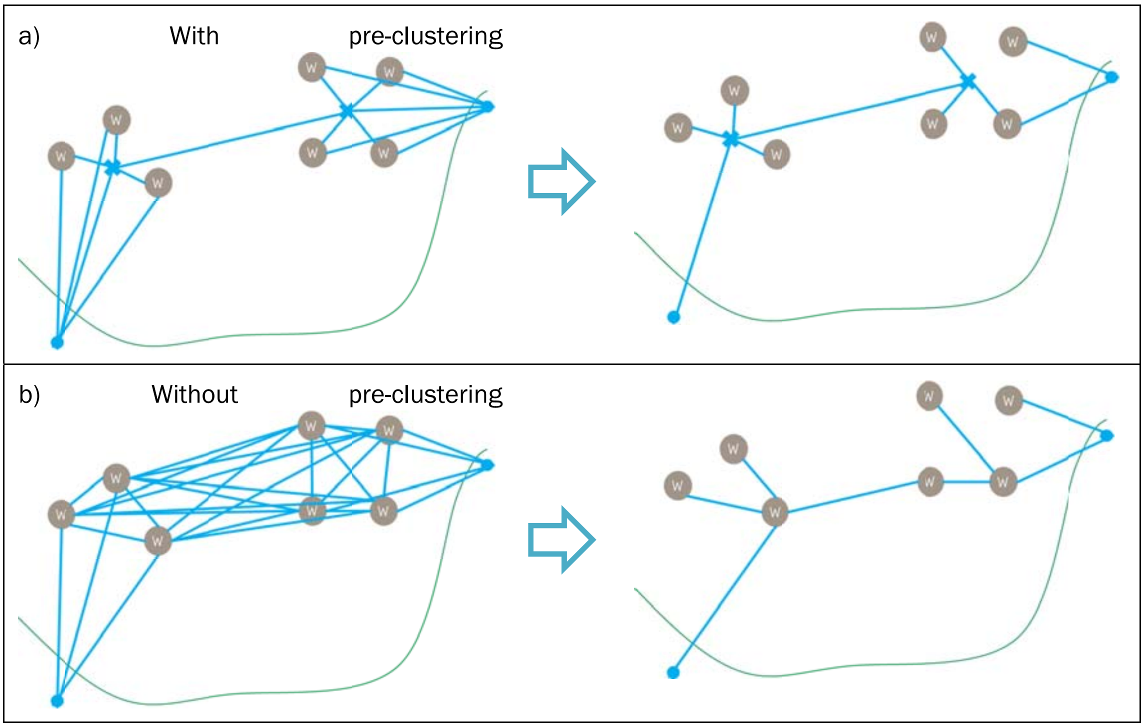

Figure 2-1: Example of grid optimisation; a) with pre-clustering; and b) without pre-clustering and all possible offshore branches included. The indicated solutions to the right are just for illustration and not based on any actual optimisation.

2.2.2 *The k-means clustering method*

The *k-means* clustering method is a common method for partitioning points into a given number of clusters, with each point belonging to the cluster with the nearest centroid.

Initially a number of "centroids" are placed at random, and clusters are generated by associating each point to the nearest centroid. For each cluster new centroids are computed based on the coordinates of all associated points. The centroid thus computed is the point that minimises the within-cluster sum of point-to-centroid distances. Then the clustering of points is repeated as above, giving a new set of clusters. This iteration is continued until no changes occur from one step to the next.

This algorithm is not guaranteed to give a global optimum and different initial choices for the centroids may yield different results. Therefore it is common to repeat the algorithm with different initial distributions.

2.2.3 *The clustering procedure*

The clustering procedure for wind farms is based on the k-means method described above. This method requires as input the number of clusters, and the clustering procedure therefore involves iteration with increasing number of clusters until the following condition is satisfied:

- Any distance from wind farm to cluster is less than a given maximum value.

Once this condition has been satisfied, it may be necessary to split clusters such that the total generation capacity within the cluster is kept within specified limits. That is, each cluster is split (if necessary) in so many parts that the following condition is satisfied.

- Total generation capacity of wind farms within each cluster is less than a given maximum value.

When a cluster is split, the division is again determined by the same k-means algorithm.

2.3 Grid connection optimisation

As discussed above, the procedure for grid connection optimisation involves a pre-processing phase that specifies allowable branches and nodes to optimise, and a MILP optimisation phase that, given the allowable choices, determines the optimal design. In the following, each of the main steps in this design procedure is described in more detail.

2.3.1 Assumptions

The optimisation step in Net-Op takes as input a set of allowable nodes and connections to choose from. Given this set, it finds the optimal selection, i.e. which nodes and connections to realise, and what the number of cables and total power capacity of the selected connections should be. In a formal sense, this does not guarantee a globally optimal solution, since the best choice may not have been included in the initial set.

Cables are technology neutral, in the sense that they are described by power capacity, loss factor and cost parameters which represent investment, installation and operation and maintenance costs. Distinctions between different cable or transmission technologies are only apparent through these parameters. Although the model is flexible in this regard, the default is to consider two kinds of nodes (AC and DC), and four different connection types:

- AC connection
- DC point-to-point connection
- DC meshed connection
- AC/DC converter

Point-to-point DC connections, connecting AC nodes with AC switchgear and a converter at each end, are from Net-Op's point of view the same as an AC connection (but with different cost and loss parameters). DC meshed connections, on the other hand, connect DC nodes, either with DC switchgear at each cable end, or in a meshed DC grid protection area with AC switchgear at each AC terminal. Again, the difference is only apparent in cost and loss parameters. The default is to assume that DC meshed connections have DC protection at each cable end.

As an extension of this, the model does not directly take into account different voltage levels. The cable cost is a linear function of power rating, and the power rating depends on the voltage level. In this sense, voltage levels are indirectly accounted for. Since voltage level is not a variable, transformer costs can only be included in a generic way as a cost that depends on power rating added to the nodal cost or branch endpoints.

These assumptions and simplifications are in part required in order to keep the optimisation problem solvable within reasonable time. However, it is also a matter of usability: A simpler model is simpler to use. More complexity in the model generally comes at the trade-off of requiring more complex input data. Since obtaining reliable data at a detailed level is very difficult, it is far from clear that such "improvements" would have any benefit for the purposes that the Net-Op tool is designed for.

More details about the Net-Op implementation are given in Section 2.4.

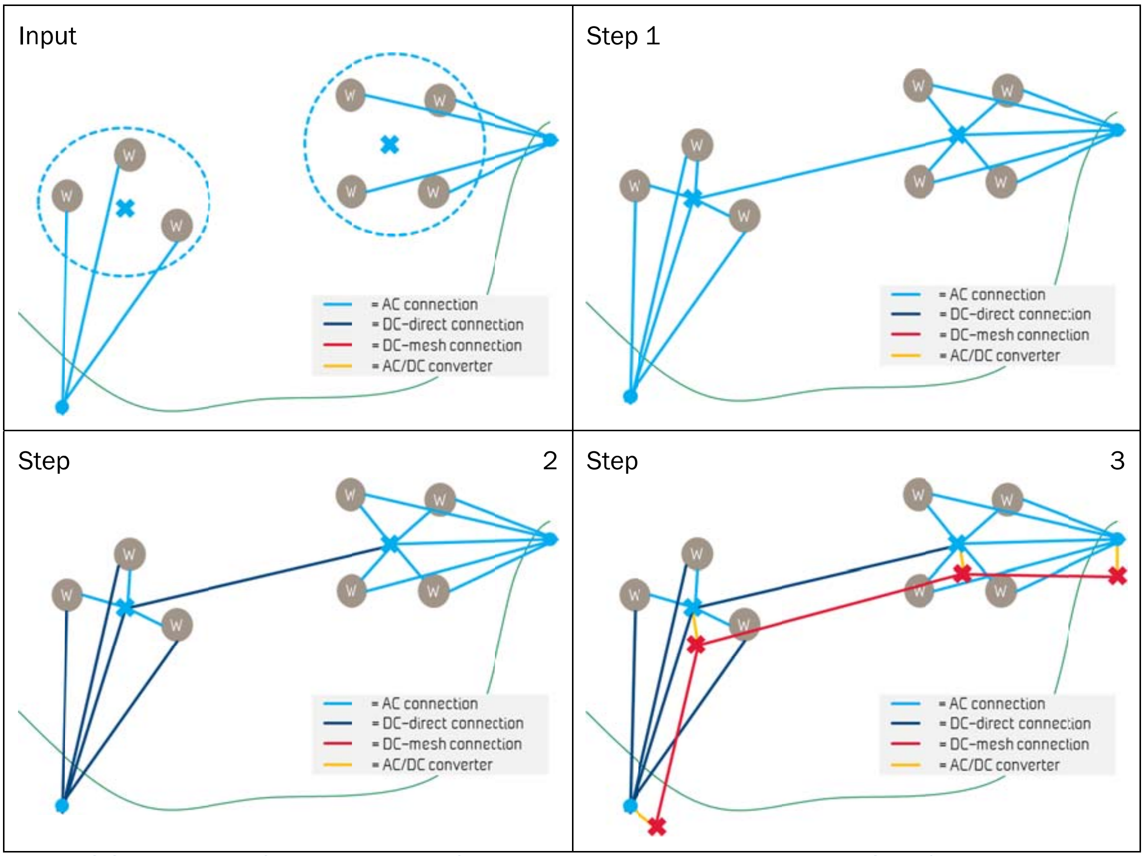

Figure 2-2: Illustration of the initial phase of the grid connection optimisation: Input; Step 1: Added connections between wind farms and clusters, between clusters and clusters to shore; Step 2: Replaced long AC branches by direct DC connections; Step 3: Added meshed DC (MTDC) alternatives.

2.3.2 Generation of allowable branches and nodes

The input to this design procedure includes the specification of offshore wind farms, including generation capacity, onshore connection points, radial connection options for each farm, and the clustering of wind farms. See Figure 2-2 part 1 for an illustration. With this starting point the procedure involves three steps in the initial phase.

Step 1: Addition of cluster connections

Additional allowable connections are added from clusters to associated wind farms, from clusters to onshore connection points (the same connection points as for the wind farms within the cluster), and between clusters. The interconnection of clusters is done such that all clusters are connected in a single network (i.e. without islands) with the minimum total cable length. This means that each cluster is connected to its nearest neighbour(s).

Step 2: Replacement of long branches by point-to-point DC alternative

The default assumption is that connections between AC nodes are AC cables. However, AC cables are only feasible up to a certain maximum distance, above which DC transmission is the only alternative.

In principle, the choice of AC versus DC cables (including a converter at each end) could be determined in the optimisation step by including both options in parallel. The choice would then be determined from the cost parameters and the required power capacity of the connection. However, this would double the number of branches to include in the optimisation, potentially increasing the computation time dramatically, as discussed previously. Moreover, the simplified cost model does not take into account technological limitations relevant for long AC cables. In other words, the choice is not simply a matter of cost of the cable itself. Long AC cables give rise to significant reactive power flow, and at some point there is a need for additional compensating devices that would give a sharp cost increase. Effectively, this means that there is a maximum feasible distance for subsea AC cables, and that AC cables are preferred below this distance and DC cables are preferred above this distance.

By making the AC versus DC decision based solely on cable length, it is assumed that the maximum distance is not dependent on cable's power capacity. In this context, the difference between AC and point-to-point DC cables is manifest only in the branch cost parameters, the branch loss factor and the branch maximum capacity. Typically, the cost of a DC alternative is significantly higher than an AC cable just below the maximum distance, due to the fact that a DC alternative includes expensive AC/DC converters at both cable ends.

Step 3: Addition of meshed DC alternative

This step generates connection alternatives involving multi-terminal DC grid(s). The fundamental difference from the "DC–direct" alternative described above, is that these "DC–mesh" cables connect DC nodes. AC/DC converters are considered as a separate class of branches that is necessary only where DC nodes are connected to AC nodes. The main benefit of a meshed DC grid over direct DC connections is that it potentially reduces the number of necessary converters. The main drawback is the need for and cost of DC circuit breakers, which are not yet a mature technology.

A meshed DC grid is only considered between clusters and from clusters to shore.

2.3.3 State sampling

What is the best grid design for an offshore wind farm cluster depends on the cost of the infrastructure and distances etc., but also on factors such as power prices at alternative onshore connection points, the distribution and variation of power demand, and the variation in wind power generation. In other words, it is not just a question of *how* to transmit, but also *where* to transmit the power. Grid investment costs are static and can be computed independently of such factors, but the operational costs of the power system depends on its operating state.

In order to account for the variability in wind generation, demand, and power prices, the approach adopted here is to select a representative sample from a time series of correlated values. This means that base values for e.g. the wind production are systematically replaced by values picked from the time series. The optimisation includes all samples, and tries to minimise the sum of the costs (including operating costs).

2.3.4 MILP optimisation

The final design step is the actual optimisation, which takes as input the allowable connections generated in the previous step and finds the design that gives the least total costs. Total costs are defined as the sum of costs for all states included in a sample (see above), and includes investment costs of branches and nodes and operational costs, i.e. the present value of the cost of generation during a specified lifetime.

This problem is formulated in standard form as a mixed integer linear programming (MILP) problem:

$$\min(C^T X) \quad \text{subject to} \quad AX \leq b, \tag{2}$$

where $X = [x, y]^T$ is a vector of continuous x and integer y state variables, C is a cost coefficient vector, and A and b represent the constraints. The output of the optimisation is the values of the state variables y. These state variables and associated cost coefficients are:

- Branch capacity (continuous) – branch cost per MW
- Branch power flow for each sample time (continuous) – no cost
- Generator output for each sample time (continuous) – marginal cost per MW
- Number of cables per branch (integer) – branch (cable) fixed cost
- Number of substations per node (integer) – node (substation) fixed cost

The constraints include equations for:

- Power balance at each node (sum of power flow into node, generation and demand equals zero)
- Generator output does not exceed available capacity
- Power flow does not exceed branch capacity
- Branch capacity is limited by number of cables
- There are no branches without a substation at each end

The formulation of the optimisation problem in standard mathematical form makes it easy to invoke a solver of choice for finding the optimal solution. Different solvers differ in their implementation, and how well each one performs depend on the actual problem. Two well-known and fast MILP solvers are the *ILOG CPLEX* solver and the *Gurobi* solver. These, however, require commercial licenses. Two open source alternatives that are freely available include the *Symphony* and *BCB* solvers in the *COIN-OR* library. A comparison of solver performances is found in ref. [5].

As stated above, the main output from the solver are values for all state variables. The results therefore specify optimal branch capacity, optimal number of cables and substations, optimal output from all generators, and power flow on all branches. This fits well with the desired output from this high-level design procedure.

The cost function (objective function) in eq. (2) is linear, and all costs are based on linear models with a fixed part and a part proportional to the state variables. For investment costs the proportional dependence is on power capacity and number of cables, whereas for operational costs, the dependence is on generator power output. Cable costs are also dependent on the distance, but since the distance of each potential connection is known, this dependence does not add computational complexity, but affects which cost parameters are needed as input from the user. More details about the problem formulation in terms of a MILP problem can be found in ref. [3].

2.4 Net-Op DTOC implementation

This section includes an overview of the Net-Op DTOC implementation and program run flow. The tool itself is project deliverable D2.1. More details can be found in the Net-Op DTOC Manual [4] (included with the tool) and in ref. [3].

Net-Op DTOC has been written as a collection of MATLAB scripts that have been complied into a command-line executable available for Windows and Linux platforms. It is in its present version a research and engineering tool, and not a polished and finished commercial product.

An outline of the run flow when using the tool is shown in Figure 2-3. The various steps have been described the previous sections of this document.

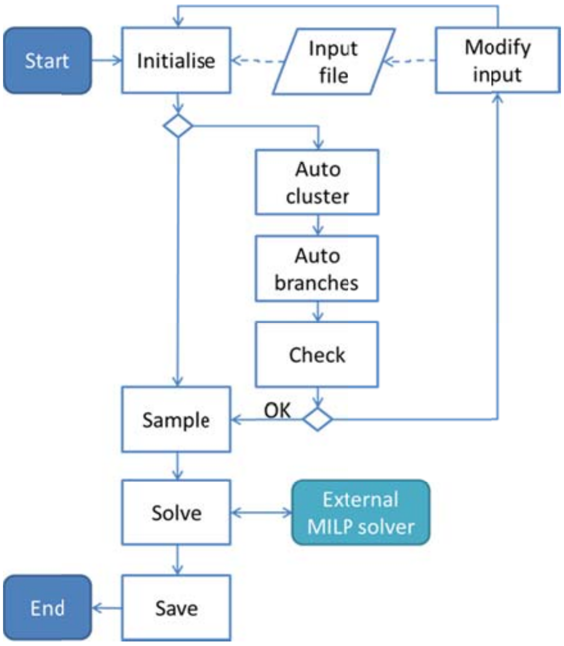

Figure 2-3: Outline of run flow using Net-Op DTOC

2.4.1 Cost Model

A central part of the case definition is the specification of cost parameters that are used to compute cost coefficients for branches and nodes. A definition of parameters used is given in Table 2.

Table 2: Description of cost parameters

Parameter	Description
B_d	Cost per distance (installation and cable)
B_{dp}	Cost per power rating and distance (cable)
B	Mobilisation cost (installation vessel)
${C^L}_p$	Cost per power rating for branch endpoint on land (onshore switchgear)
C^L	Fixed cost for branch endpoint on land
${C^S}_p$	Cost per power rating for branch endpoint at sea (switchgear on offshore platform)
${C^S}_p$	Fixed cost for branch endpoint at sea
N^L	Fixed cost of node on land
N^S	Fixed cost of node at sea
$mc_g(t)$	Generator marginal cost at time t

With these cost parameters, the total costs for a single branch are

$$\text{Single branch cost} = (B + B_d \cdot D + B_{dp} \cdot D \cdot P) + (C^{S/L} + {C^{S/L}}_p \cdot P) + (C^{S/L} + {C^{S/L}}_p \cdot P), \qquad (3)$$

where P is the power rating (capacity) and D is the branch distance. The L/S upper index indicates that the parameter depends on whether the branch endpoint is on land (L) or at sea (S). The B parameters ("costs per branch") relate to cable costs including mobilisation and installation, whereas the C parameters ("costs per endpoint") relate to cable endpoint costs such as switchgear/converters, and may differ for onshore and offshore branch endpoints.

For nodes, there is only a fixed cost per substation. This is typically interpreted as the cost of the offshore platform including typical equipment. It does *not* include the switchgear/converter costs which are considered branch type costs.

$$\text{Single node cost} = \mathrm{N}^{S/L} \tag{4}$$

Operational costs are the sum of generation cost, i.e. generator output power times generator marginal cost, for each sample time multiplied by a net present value factor that effectively transforms these costs into a capital cost that can be added to the investment cost. It is this total cost that is minimised in the optimisation procedure.

$$\text{Capitalised operational cost} = \mathrm{npv}\{\sum_{g,t} P_g(t)\, mc_g(t)\} \tag{5}$$

$P_g(t)$ is the power output of generator g at time t, and $mc_g(t)$ is its marginal cost. The sum runs over all generators and sample times. The $\mathrm{npv}\{\}$ function is a net present value function which takes into account lifetime, discount rate and sample size to get total capitalised cost of generation.

2.4.2 Grid model

The Net-Op electrical grid model is a simple transportation model where cables are described by power capacity, loss factor and cost parameters which represent investment, installation and operation and maintenance costs. Distinctions between different cable or transmission technologies are only accounted for via these parameters.

Transmission losses are included with a linear dependence on power flow. In this way, the power flow at the start end of a branch (cable or converter) is higher than the power flow at the end, i.e. at the receiving node. By default, the loss factor is computed for all branches based on generic values per distance, or generic constant values for converters.

The distance of connections is, by default, computed from the latitude and longitude coordinates of the connected nodes. However, it is possible to override this by explicitly specifying the distance (a value different from "NaN" in the case file). The same is true for the loss factor described above. Similarly, the cost parameters for a branch are computed from generic parameters, depending on cable type and distance. These parameters can also be computed separately and specified explicitly in the input case file, allowing for example extra cost for a cable that goes through an area with difficult seabed conditions.

2.4.3 Data requirements

The following data are required to perform a grid optimisation using Net-Op.

Grid data: The grid data that is required as input to run the tool consists of wind farm locations, possible onshore connection points with potential capacity constraints Wind farm locations, onshore connection points, existing grid connections with capacities, and default radial AC connections from each wind-farm to shore.

Correlated time series: To account for variability in wind power, demand and power prices, the optimisation is done on a sample of operational states, i.e. a sample from time series representing these variabilities. It is possible to omit the time series and use constant values instead, but to fully exploit the capability of Net-Op, the following correlated time series should be provided as input:

- Wind power output for each wind farm
- Power demand in each onshore price area
- Power (wholesale) prices in each onshore price area

An alternative to using a power price time series is to define multiple onshore generators with different cost of generator. Such an approach would include the feedback that wind power has on wholesale prices, but is a more complex set-up.

Cost parameters: Generic cost parameters for each branch type must be specified according to the cost model given in equations (3), (4) and (5).

Other parameters: Physical parameters such as maximum power capacity and loss factors for different branch types, maximum length for AC cables, maximum distance and power capacity within cluster.

Configuration parameters: Parameters that affect the program execution, e.g. choice of solver, and whether to show figures on the screen.

The input data is described in more detail in the manual [4].

2.4.4 User interface

The tool has a simple user interface where all user interaction is done via input and output files. The command line executable takes a case specification file (XML) as input, and completes the entire design procedure without any further user input. Results are written to files and (optionally) shown as figures on the screen.

The tool is started by the command: `netopdtoc <casefile>`, where `<casefile>` is replaced by the name of the case specification XML file.

Input files are:

- Case specification file – an XML file specifying all input parameters
- Time series file – a CSV text file with time series for relevant variables
- PSSE generic data file – a CSV text file with generic parameter values used in the generation of PSSE raw format export of the result

Output files are:

- Figures – KML files illustrating the resultant grid. These files can be opened in Google Earth/Maps.
- Load flow case – PSSE v31 raw format load flow file. This file can be used as a starting point for further analysis of the proposed electrical grid design.
- Modified case specification file – XML file which includes modifications performed in the pre-processing steps. This file can be manually modified as used as a starting point for refined, second-step optimisations (that omit the pre-processing steps).

3 COLLECTION GRID DESIGN

A high-level procedure for collection grid design has been developed and described in in detail in the D2.2 deliverable report. For completeness, a brief summary is included here. A flow-chart for the procedure is shown in Figure 3-1.

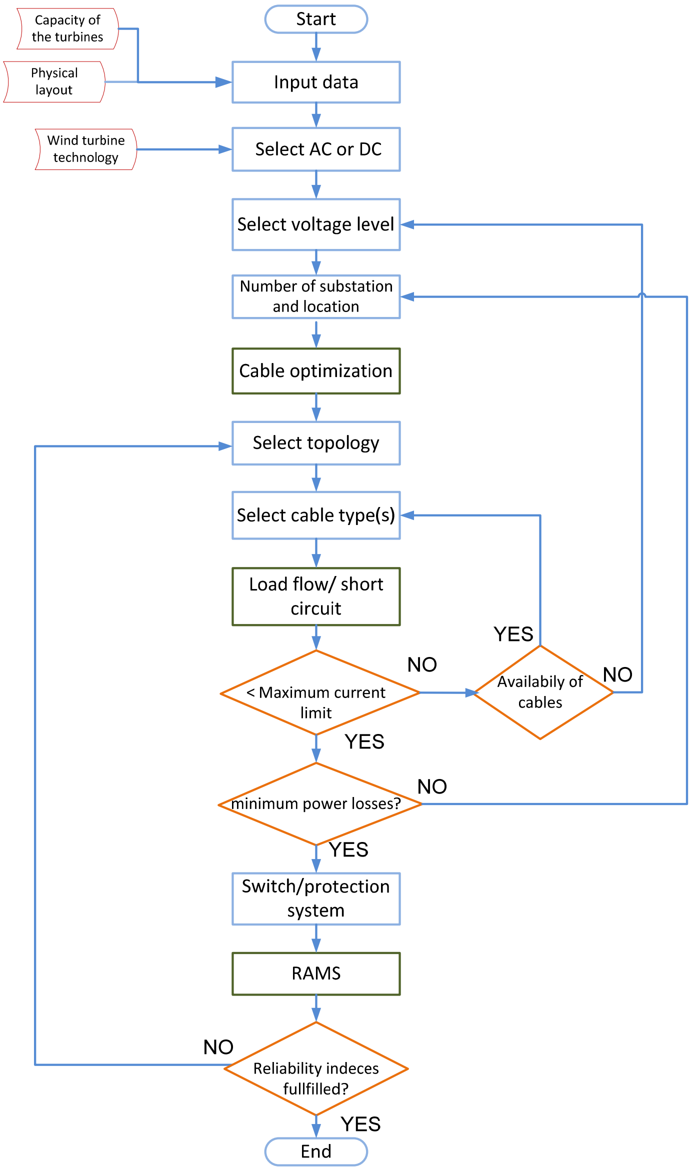

Figure 3-1: Design procedure for wind farm collection grid

Electrical design of a wind farm concerns all electrical components and how these are put together in a suitable grid structure. The overarching goal is to design an electrical system that ensures that as much as possible of the available wind power is transferred to the transmission system with as small as possible costs. The electrical design is linked to the turbine siting, and aerodynamic wake effects and electrical grid design must be seen together to ensure an optimal grid. However, the present procedure takes as input the location of the turbines. Therefore it should be used in an iterative way together with aerodynamic analysis to find suitable grid and turbine locations. There is a trade-off between aerodynamic performance and electrical performance (and cost): Longer distance between turbines gives lower wake losses but higher electrical losses and investment costs, and vice versa. Finding an economic optimum requires cost models whereby different objectives can be combined into a single objective function.

Regardless of the details of the cost modelling, it is clear that the "best" design will not have prohibitive costs, will have low electrical losses and be reliable and operate at high availability during the wind farm lifetime. It is, however, not the purpose of this report to undertake detailed comparisons based on costs and reliability, as these are very dependent on the specific situation.

The design procedure describes the overall design process, the main drivers or factors that determine the choices, the design variables and the analyses that are performed to support the design process. There are many inter-dependent design variables and it is infeasible to device a generic algorithm for making an optimal choice. Instead, the procedure focusses on describing the technical content and implications of each design variable. It is a high-level overview intended for a broad group of people without necessarily a background in electrical engineering. As such it is likely to be useful for those wanting to understand the electrical design process without going into great detail.

The main design variables that determine the type of collection grid are as follows.

AC or DC: Only AC grids are used today, but with HVDC transmission to shore, the move to DC collection grid may allow designs which avoid the offshore substation, thereby reducing the cost significantly.

Voltage level: The standard voltage level today is 33 kV, but higher voltages, such as 66 kV, are being considered. Increased voltages allow longer transmission distances and higher power, at the same time as lowering the power losses.

Number of substations: Large wind farms require multiple substations. The number is dependent on voltage level and geography of the farm.

Grid topology: The typical topology, or layout class, is radial feeders with turbines connected along strings. But increased reliability is achieved with alternatives that include some redundancy. This becomes more important for longer feeders, and where operation and maintenance activities are expensive.

Cable type: Submarine cables are available in wide ranges of cross-sections. The appropriate cable size is determined by the maximum amount of current, heating and power losses. Whether one or more cable types are used within the wind farm is a decision that takes into account the cost of installation, as each cable type may require a separate vessel.

Cable routing: The paths for the cables depend on the overall topology. Given the topology, the best cable routes are typically the ones that minimise the total cable length, yet adhere to all constraints such as forbidden areas due to e.g. other seabed infrastructure or marine life.

Protection system: The level of protection is a trade-off between reliability and cost. Since short power disruptions are of little consequence, it may be beneficial to reduce the amount of automatic protection and rely more on manual, but remotely operated switches to isolate faults.

3.1 Software tool for wind farm cable minimisation

A Matlab script for obtaining a cable layout with minimised total cable length has been made based on the Net-Op approach. The problem if formulated mathematically as a mixed integer linear programming (MILP) problem as described in previous sections, but with a simplified cost function and modified constraints. The cost function is simply the total cable distance.

This script has been described in some detail in the appendix of the D2.2 report on internal wind farm design.

The approach allows the user to specify topology (string feeders, ring feeders, unconstrained), and whether cables are allowed to cross. However, it does not take into account anything else than the total cable distance, and therefore addresses only a part of the internal wind farm grid design. Moreover, it becomes very time consuming if many wind turbines and different links are taken into consideration, for the same reasons as discussed in Section 2.1.

4 CASE STUDY

This chapter describes a case study based on wind farms in the Kriegers Flak area in the Baltic Sea at the border between Denmark, Germany and Sweden.

4.1 Case specifications

The location of wind farms included and their default, radial onshore connection points are shown in Figure 4-1.

Figure 4-1: Location of wind farms and default, radial connection points

The onshore connection points are modelled with a further grid connection to a central country node. For Sweden and Denmark this is a single connection, whereas for Germany, three different onshore connection points are connected to a central node. It is possible to include a power transmission limit on such connections, and this has been done for the Swedish connection, where power import is limited to the same amount as the total capacity of the Swedish Kriegers Flak wind farm. For Denmark and Germany, the onshore transmission capacity was considered unlimited.

At each country node, one load is included, with a power demand equal to the country's total demand, and one generator with unlimited capacity and marginal price equal to the country's power price, i.e. sampled from the time series. (In fact, with this setup, where wind power output is always smaller than the demand, it makes no difference whether demand is considered constant or variable).

It is assumed that the wind farms have an internal AC grid, so each wind farm can be represented as an AC node in the offshore grid optimisation. Details about the included wind farms are shown in Table 3.

Power time series for each wind farm was generated using DTU's CorWind model.

Table 3: Wind farm details

#	Country	Wind farm	Capacity	Latitude	Longitude	Connection point
1	DK	Kriegers Flak A K2	200	55.05	12.98	DK Ishøj
2	DK	Kriegers Flak A K3	200	54.99	12.82	DK Ishøj
3	DK	Kriegers Flak A K4	200	55.01	13.07	DK Ishøj
4	DK	Kriegers Flak B K1	200	55.08	12.87	DK Ishøj
5	DE	EnBW Baltic 2	288	54.98	13.16	DE Bentwisch
6	DE	EnBW Baltic 1	48	54.61	12.65	DE Bentwisch
7	DE	Baltic Power	500	54.97	13.22	DE Bentwisch
8	DE	Wikinger	400	54.83	14.07	DE Lubmin
9	DE	Arkona Becken Südost	480	54.78	14.12	DE Lubmin
10	SE	Kriegers Flak	640	55.07	13.10	SE Trelleborg

4.2 Assumptions and input data

This Section describes the specific assumptions used in this case study.

4.2.1 Costs

Cost parameters for offshore cables and converters, including AC switchgear and substation costs, as well as mobilisation and installation are based on numbers given in the Windspeed project [6]. Those numbers are based on 600 MW units, and it suggests proportional scaling to get costs for other power ratings.

Meshed DC grids require protection system (DC breakers) that can isolate fault in the DC network. Such equipment is not commercially available and it is therefore difficult to estimate costs. Since DC breaker technology has many similarities with AC/DC converter technology, it is natural to assume that the cost will be a not-too-small fraction of the converter cost. The cost fraction used for grid optimisations in the Windspeed project [7] was 1/3, meaning that that DC switchgear is assumed to cost one third of an AC/DC converter. The same cost fraction is assumed in this case study. Relevant cost parameters from the Windspeed project are summarised in Table 4. These parameters are used as a basis for the cost specifications for Net-Op, shown in Table 5 where proportional scaling has been assumed.

Note that converter costs have been entered in the "per endpoint" group in order to allow different values for converters on land and converters at sea. Each branch has two endpoints, so the total converter costs are therefore twice the values entered in the table, i.e. 2 × 105 = 211 k€/MW. In this case, however, it makes no difference since the onshore and offshore values are the same.

Note also that for DC-direct branches, the endpoint cost includes converter, AC switchgear, and for offshore endpoints, an offshore DC platform. DC-mesh branches have endpoints with DC switchgear, which is assumed to be 126 M€ / 3 = 42 M€ for a 600 MW unit.

The cost of a single branch connecting two AC nodes is plotted in Figure 4-2 for different branch types and power ratings as a function of cable distance. In this comparison, DC-mesh is always more expensive than DC-direct, since both alternatives have two converters, but DC-mesh uses switchgear on the DC side. The benefit of DC-mesh is only apparent in meshed grids.

Table 4: Offshore substation costs from the Windpseed project

Component	Cost	Comment
HVAC cable	2.49 M€/km	600 MW unit, includes installation
HVDC cable	0.76 M€/km	600 MW unit, includes installation
cable mobilisation	5 M€	Mobilisation of e.g. vessel
HVDC converter	126 M€	600 MW unit
AC switchgear	7.1 M€	600 MW unit
Other substation equipment	6.5 M€	Ignored in Net-Op
Offshore HVDC platform	27.6 M€	for converter, transformer, etc
Offshore HVAC platform	18.7 M€	for transformer, etc.

Table 5: Net-Op cost parameters (linear with respect to MW)

Type	Cost per branch			Cost per branch endpoint			
	B_d k€/km	B_{dp} k€/kmMW	B k€	C^L_p k€/MW	C^L k€	C^S_p k€/MW	C^S k€
AC	0	4.1	5,000	11.8	0	11.8	0
DC-mesh	0	1.27	5,000	70.0	0	70.0	0
DC-direct	0	1.27	5,000	221.8	0	221.8	27,600
converter	0	0	0	105.0	0	105.0	0

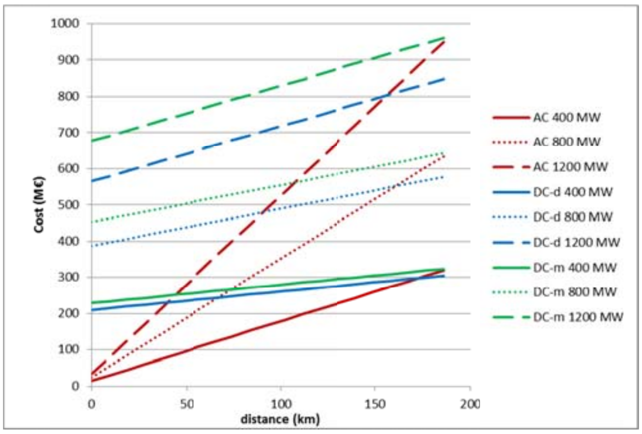

Figure 4-2: Cost of different cable types as a function of distance and power rating. DC cables include the cost of converters at both ends, but not node costs

The operational costs also need to be taken into account in the optimisation, and these are computed as the net present value of the cost of generation plus an operation and maintenance cost during a specified lifetime. The relevant parameters for computing these costs are given in Table 6.

Table 6: Parameters for capitalised operational costs

Parameter	Value	Comment
O&M rate	2 %	Operation and maintenance cost fraction relative to investment costs
Discount rate	8 %	For computing net present value of future costs
Lifetime	30 years	Duration over which to consider operational costs

4.2.2 Distance and power limitations, loss factors

The assumed maximum power rating for cables and converters is an important input since it determines the number of cables or converters that are required to transport a given amount of power. Because the branch cost includes a fixed price, an increase in the number of cables or branches leads to a step increase in the cost. The maximum distance allowed for AC branches simply determines when AC cables are considered and when DC-direct (point-to-point) are considered. As indicated in Figure 4-2, the AC alternative is typically significantly cheaper for low distances (when it is feasible). Maximum allowable values used in this case study are shown in Table 7.

Power losses are computed as a specified loss fraction times the power flow on a branch at a given time. The loss fraction in turn depends on the type of branch and on the distance (for cables), and is computed according to this equation:

$$\text{Loss fraction} = \text{constant} + \text{slope} \times \text{distance}$$

The constant and slope values used in this case study for different branch types is specified in Table 7.

Table 7: Branch specific parameters

Branch type	max distance	max power	power loss constant	slope
AC	65 km	700 MW	0	0.005 %
DC-direct		1000 MW	3.2 %	0.003 %
DC-mesh		1000 MW	0	0.003 %
converter		1000 MW	1.6 %	0

4.2.3 Time series data

The time series file includes wind power time series for 2010 for the wind farms obtained using the CorWind model. An extract of this time series, with aggregated power output of all wind farms during weeks 10 and 11 is shown in Figure 4-3.

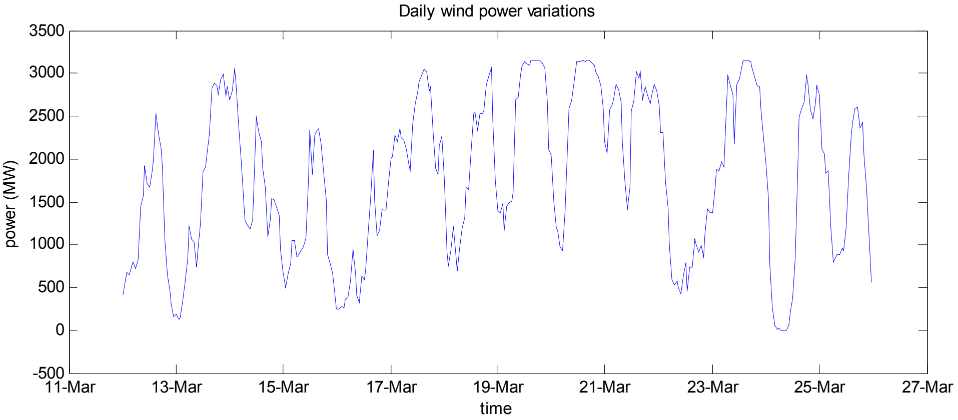

Figure 4-3: Aggregated wind power output from all wind farms during weeks 10 and 11

In addition to these, power price time series for Denmark, Sweden and Germany are specified. For Denmark and Sweden, these are obtained from hourly Nordpool[2] electricity spot prices for 2010, whereas for Germany, price time series are obtained from EEX. Power demand time series were based on the same daily and seasonal profiles as used previously by SINTEF in power market

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[2] http://www.nordpoolspot.com/Download-Centre

analyses in e.g. the TradeWind [8] and OffshoreGrid [2] projects, scaled to give the correct annual demand for 2010.

Figure 4-4: Daily price variations during weeks 10 and 11

Figure 4-4 shows an extract of the price time series (week 10–11), illustrating variations within a day and week. It is also interesting to note how the power price in Denmark sometimes drops dramatically during night-time. This is presumably because of high wind power production at a time with relatively low demand.

Weekly average values of power prices and demand are shown in Figure 4-5. Duration curves for the same variables are shown in Figure 4-6.

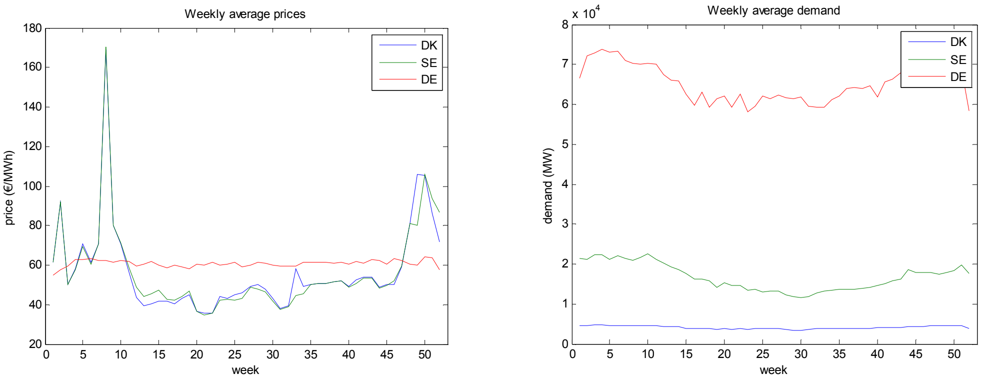

Figure 4-5: Weekly average prices (left) and demand (right) in the three price areas.

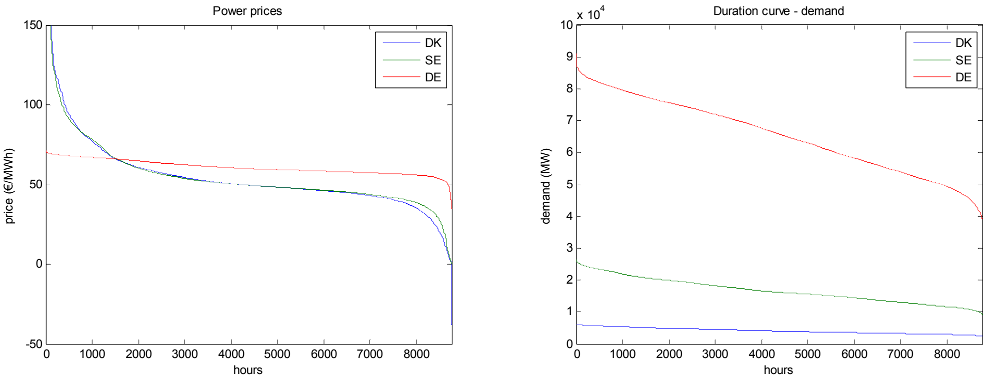

Figure 4-6: Duration curve for power prices (left) and demand (right) for the three relevant countries.

4.2.4 Other input data

The case file used for this case study is found in Appendix 6.1. The main parameters not specified above are shown in Table 8.

Table 8: Net-Op DTOC configuration

Parameter	Value	Comment
sampling algorithm	lhs_empirco	Latin Hypercube sampling of states
samples	30	Number of samples
MILP solver	symphony	COIN-OR Symphony (open source solver)
include losses	true	Take into account power losses on branches
cluster max size	20 km	Maximum distance from wind farm to cluster
cluster max power	1200 MW	Maximum generation capacity within single cluster
add DC duplicate branches	true	automatically generate DC-mesh alternative
replace AC by DC	true	automatically replace long AC branches by DC-direct branches
convert wind to negative load	true	consider wind power as negative load; if true, then wind cannot be constrained

4.3 Results

This section outlines the design process and results of the clustering and transmission grid design with the Net-Op DTOC tool based on the case specification and assumptions described above.

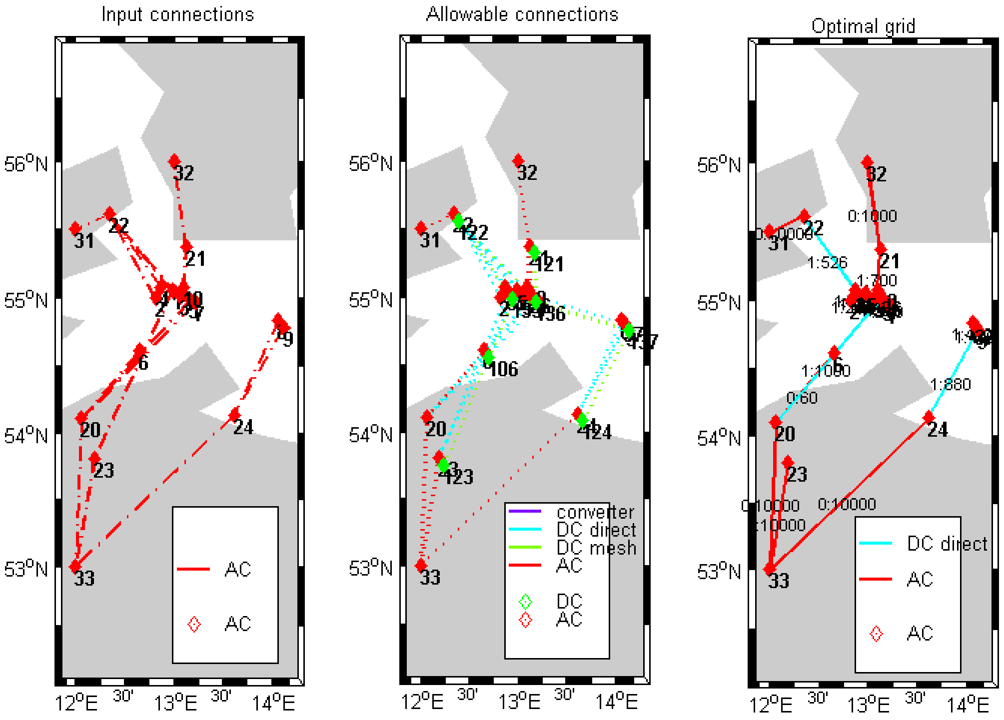

Figure 4-7: Input (left) and results (right) from the Net-Op case study simulation, as presented to the user (who can zoom in). The middle plot shows all connection options which were included in the optimalisation (automatically generated from the input).

This case study with 10 wind farm nodes, 4 onshore connection points and a sample size of 30 leads to an optimisation problem with 3191 unknowns (of which 56 are integers) and 7263 constraints. With the Symphony solver, it took 231 seconds to solve the problem (9218 iterations) on a normal office laptop computer.

Figure 4-7 shows the simulation input, the intermediate step with all allowable nodes and connections, and the optimal result.

The PSSE raw format output of the Net-Op simulation is given in Appendix 6.2. The main output from the grid optimisation, i.e. selected branches and their capacities are shown in Table 9. Some additional summary results are shown in Table 10 and Table 11.

The resulting grid has a meshed structure connecting all three countries, as shown in Figure 4-8. The Kriegers Flak area is split in two clusters with a link between. The Wikinger/Arkona Becken windfarms are kept separate from the Kriegers Flak area, as expected because of the relatively long distance.

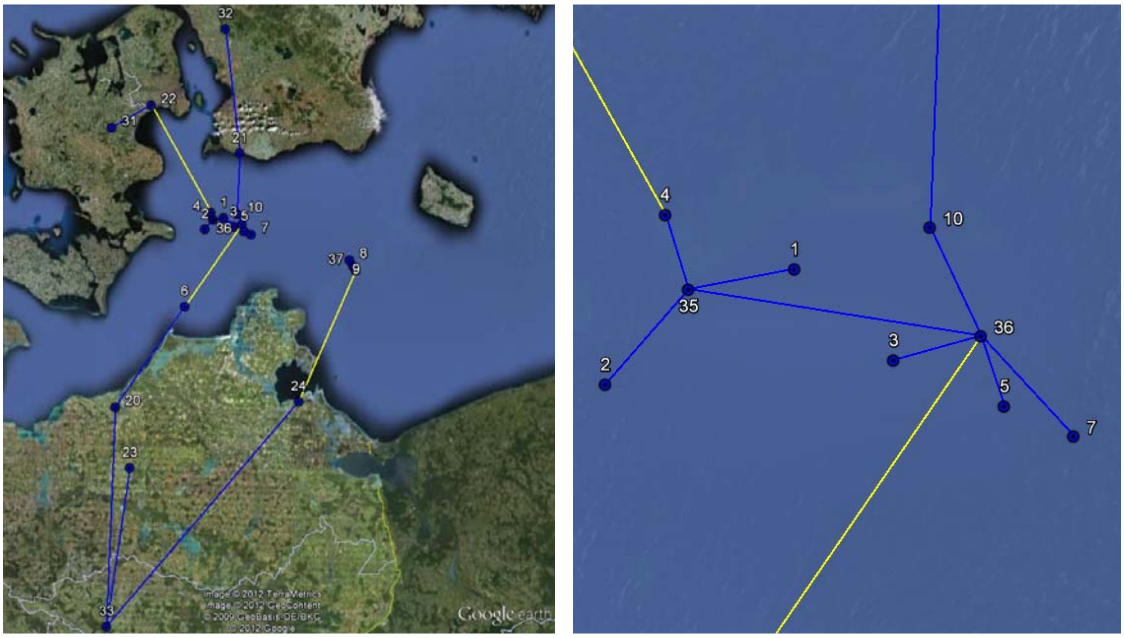

Figure 4-8: Resulting optimal grid

The Kriegers Flak area wind farms have a combined capacity of 2,276 MW. Export cables to shore have a combined capacity of 3,166 MW, so there is an over-capacity that is used to exploit the price differences in the three power markets. The solution includes a link between the two Kriegers Flak clusters with a capacity of 515 MW, and a mean power flow of 92.1 MW in the direction towards Denmark, and a mean flow of 184.2 MW from Denmark (see Table 9). This is linked to the lower power prices in Denmark than in Germany.

Table 9: Case study branch summary

from	to	cable type	loss fraction	distance	new cables	total capacity	cost (M€)	mean flow 1->2	mean flow 2->1
4	22	3	3.406 %	68.5	1	526	829	291.9	113.2
6	20	1	0.340 %	68.0	0	60	0	20.4	0.0
9	24	3	3.437 %	79.1	1	880	1138	380.2	0.1
10	21	1	0.169 %	33.9	1	700	348	350.6	164.7
20	33	1	0.001 %	123.0	0	10,000	0	724.8	64.2
21	32	1	0.001 %	70.1	0	1,000	0	350.0	164.7
22	31	1	0.001 %	25.3	0	10,000	0	282.0	113.2
23	33	1	0.001 %	90.3	0	10,000	0	0.0	0.0
24	33	1	0.001 %	165.6	0	10,000	0	367.1	0.1
1	35	1	0.029 %	5.9	1	200	48	92.8	0.0
2	35	1	0.034 %	6.9	1	200	55	90.2	0.0
3	36	1	0.025 %	5.0	1	200	41	92.4	0.0
4	35	1	0.021 %	4.3	1	522	53	129.8	220.5
5	36	1	0.020 %	4.0	1	288	39	134.6	0.0
7	36	1	0.037 %	7.4	1	500	79	234.7	0.1
8	37	1	0.019 %	3.7	1	400	42	196.8	0.1
9	37	1	0.015 %	3.0	1	400	36	0.1	196.8
10	36	1	0.033 %	6.6	1	700	84	257.8	142.3
36	35	1	0.081 %	16.2	1	515	156	92.1	184.2
36	20	3	3.570 %	123.3	1	1,000	1558	732.7	66.3

Table 10: Case study power demand (load) in MW

country	node	sample max	sample min	sample mean
DK	31	5,854	2,551	4,111
SE	32	25,049	9,660	16,703
DE	33	83,631	42,485	65,476

Table 11: Case study power generation summary

node	capacity (MW)	mean output (MW)	mean cost (€/MWh)	capacity factor
1	200	93	0	46.4 %
2	200	90	0	45.1 %
3	200	92	0	46.2 %
4	200	92	0	46.0 %
5	288	135	0	46.7 %
6	48	20	0	42.4 %
7	500	235	0	46.9 %
8	400	197	0	49.2 %
9	480	183	0	38.2 %
10	640	302	0	47.1 %
31	7000	3942.4	54.3	56.3 %
32	27000	16517.9	56.4	61.2 %
33	91000	64449.2	60.9	70.8 %

5 CONCLUSIONS

Net-Op DTOC is a tool for clustering and grid connection optimisation of offshore wind farms, suited for high-level automated offshore grid planning on a strategic level. The approach takes into account investment costs, variability of wind/demand/power prices, and the benefit of power trade between countries/price areas.

The tool itself has been described in some detail, including the underlying philosophy, required input data, and the more or less step by step design procedure it automates.

The tool was then applied to a case study consisting of wind farms in the Kriegers Flak area in the Baltic Sea between Denmark, Sweden and Germany, with the emphasis on illustrating the use of the design tool rather than the detailed results.

A procedure for electrical design of the internal wind farm collection grid was presented briefly. Together, this addresses electrical design from the offshore "supergrid" level to the wind turbine level.

6 APPENDIX

6.1 Case study XML case file

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6.2 PSSE raw format file output

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9,  'bus9',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
10,  'bus10',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
20,  'bus20',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
21,  'bus21',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
22,  'bus22',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
23,  'bus23',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
24,  'bus24',  170.000000,  1,  1,  1,  1,  1.000000,  0.000000
31,  'bus31',  60.000000,  2,  1,  1,  1,  1.000000,  0.000000
32,  'bus32',  60.000000,  2,  1,  1,  1,  1.000000,  0.000000
33,  'bus33',  380.000000,  3,  1,  1,  1,  1.000000,  0.000000
35,  'bus35',  380.000000,  1,  1,  1,  1,  1.000000,  0.000000
36,  'bus36',  380.000000,  1,  1,  1,  1,  1.000000,  0.000000
37,  'bus37',  380.000000,  1,  1,  1,  1,  1.000000,  0.000000
0 / end of bus data, begin load data
31,  1,  1,  1,  1,  4111.264854,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
32,  1,  1,  1,  1,  16703.085486,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
33,  1,  1,  1,  1,  65476.739076,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
1,  1,  1,  1,  1,  -92.774102,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
2,  1,  1,  1,  1,  -90.200988,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
3,  1,  1,  1,  1,  -92.413318,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
4,  1,  1,  1,  1,  -92.001629,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
5,  1,  1,  1,  1,  -134.503310,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
6,  1,  1,  1,  1,  -20.361396,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
7,  1,  1,  1,  1,  -234.628553,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
8,  1,  1,  1,  1,  -196.765138,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
9,  1,  1,  1,  1,  -183.409168,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
10,  1,  1,  1,  1,  -301.587921,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1
 0 /End of Load data, Begin Fixed shunt data
 0 /End of Fixed shunt data, Begin Generator data
31,  1,  3942.443145,  0.000000,  9999.000000,  -9999.000000,  1.000000,  0,  100.000000,  0.000000,  1.000000,
0.000000,  0.000000,  1.000000,  1,  100.000000,  7000.000000,  0.000000,  1,  1.000000
32,  1,  16517.853705,  0.000000,  9999.000000,  -9999.000000,  1.000000,  0,  100.000000,  0.000000,  1.000000,
0.000000,  0.000000,  1.000000,  1,  100.000000,  27000.000000,  0.000000,  1,  1.000000
33,  1,  64449.194763,  0.000000,  9999.000000,  -9999.000000,  1.000000,  0,  100.000000,  0.000000,  1.000000,
0.000000,  0.000000,  1.000000,  1,  100.000000,  91000.000000,  0.000000,  1,  1.000000
0 / end of generator data, begin branch data
10,  21,  '1',  0.000000,  0.033877,  0.000000,  700.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  33.876754,  1,  1.000000
21,  32,  '1',  0.000000,  0.070146,  0.000000,  1000.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  0.000000,  1,  1,  70.145982,  1,  1.000000
22,  31,  '1',  0.000000,  0.025274,  0.000000,  10000.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  0.000000,  1,  1,  25.273678,  1,  1.000000
23,  33,  '1',  0.000000,  0.090271,  0.000000,  10000.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  0.000000,  1,  1,  90.270707,  1,  1.000000
24,  33,  '1',  0.000000,  0.165614,  0.000000,  10000.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  0.000000,  1,  1,  165.613873,  1,  1.000000
1,  35,  '1',  0.000000,  0.005896,  0.000000,  200.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  5.896110,  1,  1.000000
2,  35,  '1',  0.000000,  0.006887,  0.000000,  200.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  6.886964,  1,  1.000000
3,  36,  '1',  0.000000,  0.004956,  0.000000,  200.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  4.956044,  1,  1.000000
4,  35,  '1',  0.000000,  0.004262,  0.000000,  522.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  4.262234,  1,  1.000000
7,  36,  '1',  0.000000,  0.007447,  0.000000,  500.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,
0.000000,  1,  1,  7.447220,  1,  1.000000
0 / end of branch data, begin transformer data
0 / end of tranformer data, begin area interchange data
0 / end of area interchange data, begin 2-terminal DC data
0 / end of 2-terminal DC data, begin VDC DC data
"DC-VSC 1",  1,  4.400000,  1,  1
4,  1,  1,  170.000000,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.000000,  9999.000000,
-9999.000000,  0,  100.000000
22,  2,  1,  -178.767576,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.0000000
"DC-VSC 2",  1,  4.400000,  1,  1
9,  1,  1,  170.000000,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.000000,  9999.000000,
-9999.000000,  0,  100.000000
24,  2,  1,  -380.104343,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.0000000
"DC-VSC 3",  1,  4.400000,  1,  1
36,  1,  1,  380.000000,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.000000,  9999.000000,
-9999.000000,  0,  100.000000
20,  2,  1,  -666.385377,  1.000000,  0.000000,  0.000000,  0.000000,  0.000000,  0.000000,  1.0000000
0 /End of VSC dc line data, Begin Impedance correction table data
0 / end of tranformer impedance correction data, begin multi-terminal DC data
0 / end of multi-terminal DC data, begin multi-section line data
0 / end of multi-section line data, begin zone data
1 ''DefaultZone''
0 / end of zone data, begin interarea transfer data
0 / end of interarea transfer data, begin owner data
1 ''DefaultOwner''
0 / end of owner data, begin FACTS device data
0 /End of FACTS device data, Begin Switched shunt data
0 /End of Switched shunt data. End of File
```

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