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Planning Tool for Clustering and Optimised Grid Connection of Offshore Wind Farms

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Abstract

A planning tool for clustering and optimised grid connection of offshore wind farms is presented and described in some detail. This tool is suitable for high level, strategic planning of clustering and grid connection of future offshore wind farms that are planned in the proximity of each other. This tool is an upgraded version of a previously developed tool for offshore grid expansion planning. The use of the upgraded tool is demonstrated with an example that considers the Kriegers Flak area, with results indicating benefits of interconnecting wind farms across country borders and using a hybrid AC and DC transmission system to shore.

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Keywords: wind farm clustering, grid connection, Net-Op, EERA-DTOC

1. Introduction

Many large offshore wind farms are planned in the proximity of each other and in regions where it is natural to consider wind farm grid connection together with power exchange links between different countries. The design of a coordinated offshore grid that reduces the overall costs, however, involves many stakeholders with potentially conflicting objectives, and may be constrained by regulatory frameworks. This paper describes a planning tool that is suitable for high level strategic planning of wind farm clustering and grid connection in an early phase before more detailed analysis is performed. The tool is an adaptation and extension of a previously developed offshore grid expansion planning tool named Net-Op [1]. The new functionality makes it suitable for analysis of clustering and within-cluster grid layout as well as larger scale offshore grid design. The application of the tool is demonstrated with an example case.

A current effort in the European EERA-DTOC project[1] aims to combine this and other wind farm design tools into a multidisciplinary integrated software tool for an optimised design of offshore wind farms and clusters of wind farms, the *Design Tool for Offshore wind farm Clusters* (DTOC) [2, 3].

Grid connection of offshore wind farms differs 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 to onshore

[1] www.eera-dtoc.eu

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connection points for many planned wind farms brings with it technological challenges, but also new possibilities regarding grid layout; when distances are large it is increasingly relevant to consider the wind power grid connection in tandem with power trade possibilities. An obvious idea 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 solution whereby the demand is covered by the cheapest possible mode of production. The comparison between investment costs of 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 and financial details. It is aimed at long-term planning at a high-level by users such as government and government agencies, transmission grid operators and academia. It is fairly easy to use and requires a modest amount of input data.

The main modifications to Net-Op which has made it suitable for this type of application is the capability to consider multiple cable types (AC/DC); the implementation of automated pre-processing which includes a clustering algorithm and an algorithm to select which branches and branch types to include in the design process; improved interface to external solvers and improved data export functionality. The tool is written using Matlab, but compiled into a stand-alone command-line executable.

2. The Net-Op design procedure

Offshore wind farm clustering and grid connection design are interlinked and require 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 is formulated by means 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 then determines which connections to realise, and what their power capacities should be.

Potential nodes and branches have 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. number of branches and nodes. Since there are many ways to connect a given number of nodes, the number of possible

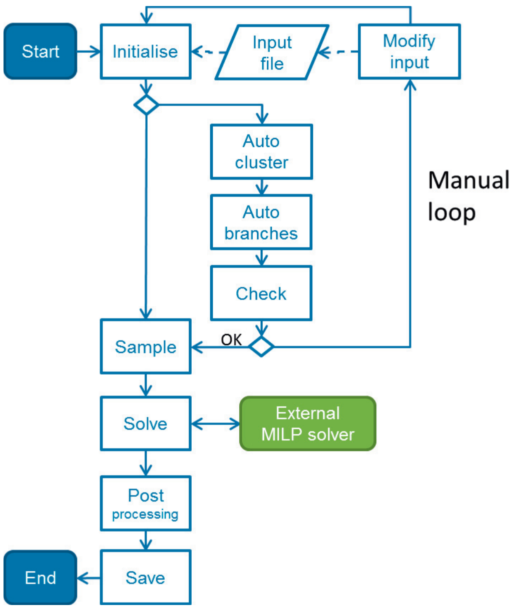


Fig. 1: Net-Op design process

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 a number of possible combinations C equal to

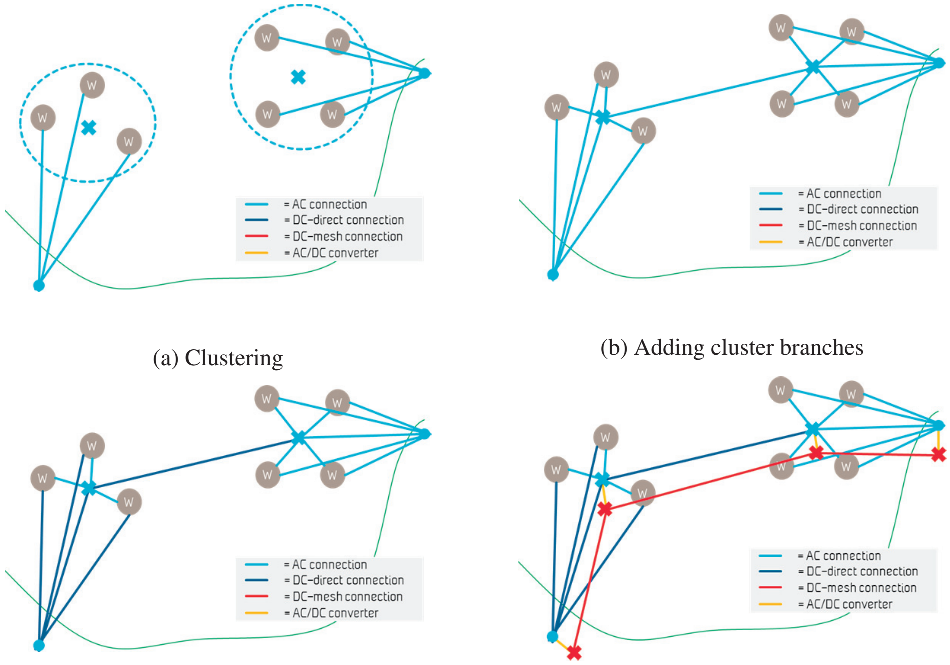
$$C = \sum_{b=0}^{B} \binom{B}{b} = 2^B, \tag{1}$$

if 0 or 1 cable is considered. Since there can be multiple cables in parallel, the true number of combinations increases even faster than indicated by the above expression. 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. In order to limit the number of branches to consider in the optimisation, a subset denoted the *allowable branches* are therefore specified explicitly.

The 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. These considerations motivate a split in the automated design process, with the initial preprocessing phase aiming to suggest cluster nodes and select allowable branches, and the final phase specifying and solving the MILP problem. The automated preprocessing steps have been implemented in the upgraded Net-Op tool and are described in more detail in the following. An overview of the Net-Op design process is shown in Fig. 1.

2.1. Clustering

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. 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



(a) Clustering

(b) Adding cluster branches

(c) Replacing long AC by DC–direct

(d) Adding DC–mesh

Fig. 2: Automated pre-processing for generating a suitable set of allowable connections for the optimisation

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 to consider.

The clustering procedure is based on the *k-means* method, which is a common method for partitioning points into a given number of clusters, with each point belonging to the cluster with the nearest centroid. Since the k-means method requires as input the number of clusters, the procedure involves an iteration with increasing number of clusters until all wind farms to cluster distances are less than a given maximum value. Once this condition has been satisfied, clusters are split, if necessary, such that the total generation capacity within the cluster is less than a given maximum value. When a cluster is split, the division is again determined by the k-means algorithm.

2.2. Generation of allowable connections

After the wind farms have been grouped in clusters as described above (Fig. 2a), the program has the option of automatically generating a set of allowable branches. This involves three steps as described in the following and illustrated in Fig. 2. It is assumed that at least a radial connection from each wind farm to shore has been specified in the input files by the user.

Step 1: Addition of cluster connections (Fig. 2b). 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 (Fig. 2c). 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 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 whereas DC cables are preferred above this distance.

Step 3: Addition of meshed DC alternative (Fig. 2d). 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. Them 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. State sampling

The optimal 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 the power to shore at the lowest cost, 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 by Net-Op 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) for the entire sample.

2.4. Optimisation

The final design step is the actual optimisation, which takes as input the allowable connections 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 [1].

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

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

where $X = [x_c, x_p, x_g, y_b, y_n]^T$ 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 main output of the optimisation is the values of the state variables. These state variables and associated cost coefficients are:

- x_c = branch capacity – branch cost per MW
- x_p = branch power flow for each sample time – no cost (but power losses)
- x_g = generator output for each sample time – generation cost per MW
- y_b = number of cables/converters per branch – fixed cost per cable/converter
- y_n = number of substations per node – fixed cost per node (offshore substation)

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 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. More details about the general problem formulation and cost model is found in ref. [1].

The formulation of the optimisation problem in standard mathematical form makes it easy to invoke a solver of choice for finding the optimal solution. A comparison of solver performances is found in ref. [4].

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.

3. Data requirements

3.1. 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. The present implementation considers two kinds of nodes (AC and DC), and four different connection types: 1) AC cable, 2) DC point-to-point cable (DC–direct), 3) DC cable for meshed grids (DC–mesh), and 4) AC/DC converter.

The model does not directly take into account different voltage levels. However, since the cable cost is a linear function of power rating, and the power rating depends on the voltage level, the voltage level is indirectly accounted for. Transformer costs are not considered.

3.2. Cost model

Costs of branches, nodes and generation (operational cost) are specified by the following linear cost functions.

$$\text{cost of branch} = (B + B_d \cdot D + B_{dp} \cdot D \cdot P) + \sum_{i=1,2} (C^{b_i} + C_p^{b_i} \cdot P), \tag{3}$$

$$\text{cost of node} = N^n, \tag{4}$$

$$\text{cost of generation} = \text{NPV}\Big\{P_g(t) \cdot mg_g(t)\Big\}. \tag{5}$$

Here, D is branch distance, P is branch power capacity; B, B_d and B_{dp} are cost parameters that describe branch costs; and C and C_p are cost parameters associated with each branch endpoint. Branch endpoint costs may depend on whether the endpoint is onshore or offshore, which is indicated by the superscripts $b_i \in \{\text{offshore}, \text{onshore}\}$. The node cost N is just a fixed value that may depend on whether the node is onshore or offshore, $n \in \{\text{offshore}, \text{onshore}\}$. The parameter $mg_g(t)$ is the marginal cost of a generator at sample time t, and $P_g(t)$ is its power output. NPV refers to the *net present value* function. Total costs are obtained by summing costs for all branches, nodes and generators. Different types of branches, nodes and generators have different values for these cost parameters.

3.3. Input data

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, 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 from correlated 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 normally 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 capacities and marginal costs, representing the area's generation mix. Such an approach would include the feedback that wind power has on wholesale prices, but is a more complex set-up. A power demand time series is only relevant if the generation is specified in this way, or if the demand is so low that it may constrain the wind power output.

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.

4. Example: Kriegers Flak

To demonstrate the use of the tool, this Section considers 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 included wind farms and their "default" radial connection points are listed in Table 1. These are existing and planned wind farms in the Kriegers Flak area and in the Wikinger/Arkona Becken area farther east.

Cost parameters for the different connection types are based on ref. [5] and shown in Table 2 for branches. The cost of nodes is assumed to be 18.7 M for offshore AC nodes and 27.6 M for offshore DC nodes, and zero for onshore nodes. Power losses are considered to be 0.005 %/km for AC cables and 0.003 %/km for DC cables. Converters are assumed to have power loss of 1.6 %. The maximum capacity of AC cables is assumed to be 700 MW, and for DC cables and converters 1000 MW. Maximum length of AC cables is assumed to be 65 km. The maximum distance between wind farm and cluster node is specified as 20 km. Maximum power rating within a single cluster is specified as 1200 MW.

The time series file includes wind power time series for 2010 for each wind farm, obtained[2] using DTU's CorWind model [6]. In addition to these, power price time series for Denmark, Sweden and Germany have been used. For Denmark and Sweden, these were obtained from hourly Nordpool[3] electricity spot prices for 2010, whereas for Germany, price time series are obtained from EEX[4]. Power demand time series were based on the same daily and seasonal profiles as used previously by SINTEF in power maket analyses in e.g. the TradeWind [7] and OffshoreGrid [8] projects, scaled to give the correct annual demand for 2010.

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[2]Thanks to Nicolaos A. Cutululis at DTU
[3]`http://www.nordpoolspot.com`
[4]`http://www.eex.com`

Table 1: Wind farms

#	Country	Wind farm	Capacity	Latitude	Longitude	Connection point
1	DK	Kriegers Flak A K2	200	55.05	12.98	DK Ishj
2	DK	Kriegers Flak A K3	200	54.99	12.82	DK Ishj
3	DK	Kriegers Flak A K4	200	55.01	13.07	DK Ishj
4	DK	Kriegers Flak B K1	200	55.08	12.87	DK Ishj
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 Sdost	480	54.78	14.12	DE Lubmin
10	SE	Kriegers Flak	640	55.07	13.10	SE Trelleborg

Table 2: Branch cost parameters

Type	B_d k/km	B_{dp} k/kmMW	B k	C_p^L k/MW	C^L k	C_p^S 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

4.2. Results

This case study with 10 wind farm nodes, 4 onshore connection points and a sample size of 30 gave an optimisation problem with 3191 unknowns (of which 56 are integers) and 7263 constraints.

With the *Symphony* MILP solver, it took 231 seconds to solve the problem (9218 iterations) on a normal office laptop computer. Fig. 3 shows the simulation input, the intermediate step with all allowable nodes and connections, and the optimal result as presented to the user.

The main output from the grid optimisation, i.e. selected branches and their capacities are shown in Table 3. The resulting grid has a meshed structure connecting all three countries, as shown in Fig. 4. 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.

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 optimal grid design 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 3). This is linked to the fact that power prices are lower in Denmark than in Germany.

It should be stressed that this case study is presented here primarily to demonstrate the capability of the planning tool, and that changes in the input variables will give different results. In a real application, it is likely to be of high interest to run the program for a set of different input variables to get an indication of sensitivity to different parameters.

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 an outline of the step by step design procedure it automates.

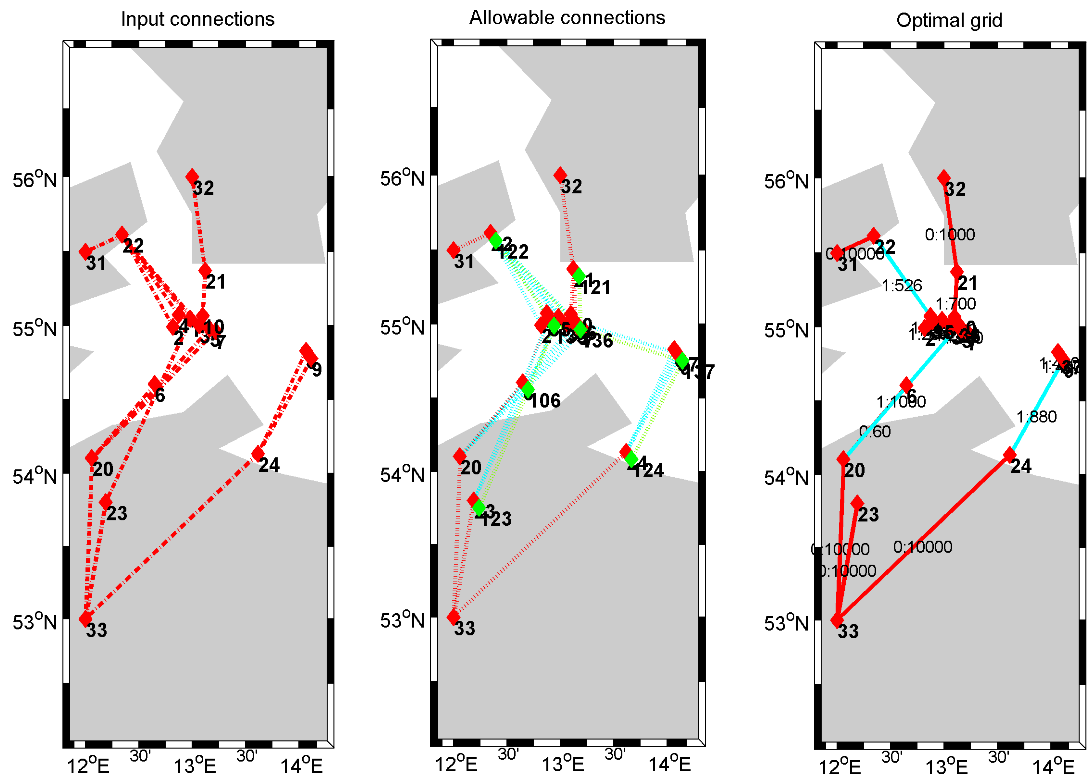
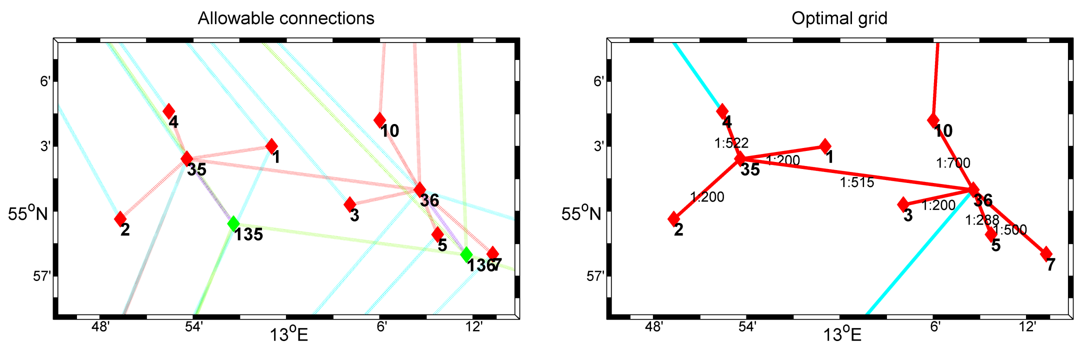


Fig. 3: Kriegers Flak example showing input (left), the set of allowable connections considered in the optimisation (middle), and the resulting optimal grid (right). Red lines are AC, cyan are DC–direct, and green are DC–mesh. Numbers indicate node numbers, and optimal number of cables and capacity of branches.



(a) Allowable nodes and branches (b) Optimal grid

Fig. 4: Grid options and result; zoomed in on the Kriegers Flak wind farm area.

Table 3: Key results from example case. Wind farm nodes are indicated by (w), cluster nodes by (c1–3) and onshore nodes by the country code (de/se/dk).

Node from	Node to	Distance (km)	Cable type	Number	Capacity (MW)	Mean flow → (MW)	Mean flow ← (MW)
4 (w)	22 (de)	68.5	DC	1	526	291.9	113.2
6 (w)	20 (dk)	68	AC	0	60	20.4	0
9 (w)	24 (de)	79.1	DC	1	880	380.2	0.1
10 (w)	21 (se)	33.9	AC	1	700	350.6	164.7
20 (de)	33 (de)	123	AC	0	10000	724.8	64.2
21 (se)	32 (se)	70.1	AC	0	1000	350	164.7
22 (dk)	31 (dk)	25.3	AC	0	10000	282	113.2
24 (de)	33 (de)	165.6	AC	0	10000	367.1	0.1
1 (w)	35 (c1)	5.9	AC	1	200	92.8	0
2 (w)	35 (c1)	6.9	AC	1	200	90.2	0
3 (w)	36 (c2)	5	AC	1	200	92.4	0
4 (w)	35 (c1)	4.3	AC	1	522	129.8	220.5
5 (w)	36 (c2)	4	AC	1	288	134.6	0
7 (w)	36 (c2)	7.4	AC	1	500	234.7	0.1
8 (w)	37 (c3)	3.7	AC	1	400	196.8	0.1
9 (w)	37 (c3)	3	AC	1	400	0.1	196.8
10 (w)	36 (c2)	6.6	AC	1	700	257.8	142.3
36 (c2)	35 (c1)	16.2	AC	1	515	92.1	184.2
36 (c2)	20 (de)	123.3	DC	1	1000	732.7	66.3

The tool was applied to an example case 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. With this caveat in mind, the results indicate benefits of interconnecting wind farms across country borders and using a hybrid AC and DC transmission system to shore.

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