OffshoreDC WP-5 :

Offshore Grid Design and Market Impact – Preliminary Results

Vin Cent Tai, Kjetil Uhlen, and Juha Kiviluoma

Summary – This report presents the offshore grid design process developed for the OffshoreDC project WP – 5. The case study presented in this report is the offshore grid scenario for year 2030. The aim of this work is to serve as a guideline for future offshore grid planning. The input data and preliminary results are also presented in this report.

I. Introduction

The geographical extent in the study is the Baltic Sea region and the time horizon is 2030. The power systems of Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Germany and Denmark are included in this study. Scenarios for wind power, other generation, load, onshore grid reinforcements and different offshore grid topologies are defined in this work. There are 12 price areas in total: 4 in Sweden (designated SE1 – SE4), 1 in Finland (FI), 2 in Denmark (DK1 and DK2), 1 in Germany (DE), 1 in Poland (PO), 1 in Estonia (EE), 1 in Lithuania (LI) and 1 in Latvia (LT). Total wind farms included in this study is 97 and the number of onshore substations is 19.

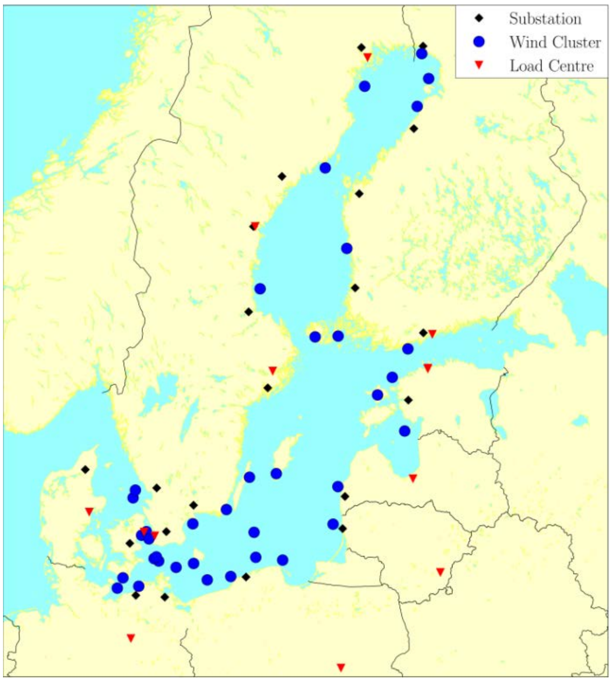

Fig. 1. Location of wind farms, onshore substations, and load centres for the case study.

II. Design process

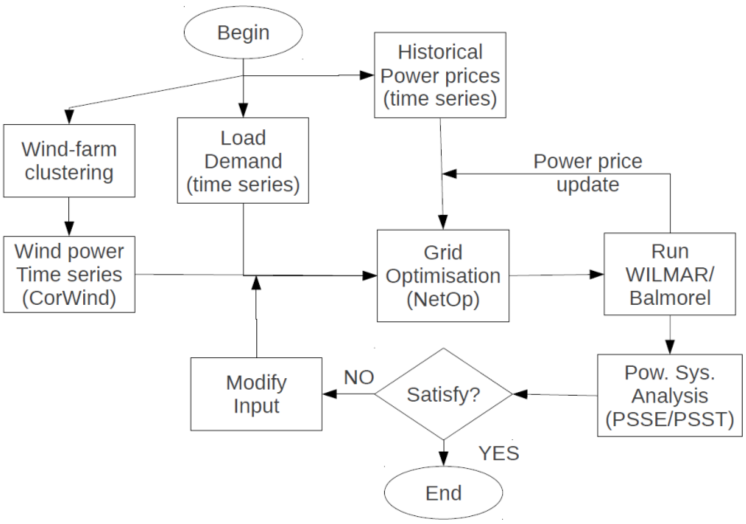

Fig. 2. The offshore grid design flow chart

This section describes the design process flow and the tools required as depicted in Fig. 2. Three sets of input data are required for the grid design: i.) wind farm data (locations and wind power productions); ii.) load demands, and; iii.) power prices at each price area. How the wind power will affect the future power prices is not known without the grid layout. Therefore historical data of power prices is used in the initial design. The results from the initial run (e.g. the mean power flow from one point to another) will then be used in conjunction with the market model tool (WILMAR/Balmorel) to update power prices and the grid design. The grid topology will then be analysed using the power system analysis tools such as PSS/T or PSS/E.

a. Grid Optimisation

The optimisation tool used in this study is *NetOp* (Network Optimisation tool) developed at SINTEF – NTNU for high level strategic planning of wind farm clustering and grid connection [Svendsen13]. It is capable of finding an optimal grid structure by taking into account the wind power variations, stochastic power prices, and load and generation scenarios (onshore and offshore). The results of the optimisation are which cables to be built alongside with the type and capacity of the cables.

The network optimisation is formulated as a Mixed Integer Linear Programming (MILP) problem in NetOp, with the following cost function:

$$\min(C_{Tot}^{bran} + C_{Tot}^{node} + C_{Tot}^{geno})$$

where, C_{Tot}^{bran}, C_{Tot}^{node}, and C_{Tot}^{geno} are the total branch cost, total node (platform) cost, and total cost of generation, respectively. The cost models implemented in NetOp are linear models.

b. Clustering of Wind farms

The objective of wind farm clustering is to reduce the number of the number of nodes in the optimisation process, thereby reduce the excessive computation time. This is due to the fact that the number of possible connections between the nodes increases exponentially with the number of nodes, as depicted in Fig. 3.

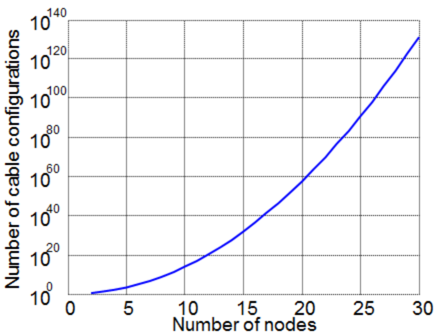

Fig. 3. The number of possible connections increases exponentially as the number of nodes increases.

The following criteria were used to generate the wind farm clusters:

- The wind farms that belong to the country that owns them
- The size of the cluster is ±100km
- The maximum power of the cluster is ±2000MW
- The location of the wind cluster is the centroid of the wind farms

As a result from the clustering procedure, the number of wind farm nodes has been reduced to 32.

c. Market model

The impact of wind power on power market is not yet performed at this stage. The market tools suggested for market modelling are WILMAR [NorheimEA05] and Balmorel [Balmorel01].

d. Power system analysis

The power system analysis will be carried out after the market analysis. The power system tools suggested for the power system analysis are PSS/E and PSS/T.

III. Input Data

This section describes the models used and assumptions made for the optimisation process. Note that some quick assumptions made for the inputs at this stage are not realistic as the work performed at this stage is only to demonstrate the concept of the grid design process discussed earlier.

a. Wind Power Model

The assumption made for the wind power model at this stage is the wind power generation profile is the same across the Baltic Sea. This assumption is not realistic, and the CorWind [Sørensen09] model will be used in the future work.
The current wind power time series data is obtained by using the time series data for wind farms in the Krigersflak area [Svendsen13]. The data is then scaled to meet the expected wind power production of each country in 2030. The expected total installed capacities in the Baltic Sea for each country are presented in Table 1.

Table 1. Total wind power installed capacity in the Baltic Sea for each country by 2030. Data extracted from TWENTIES [CutululisNA] report for the high scenario.

#	Country	Installed Capacity [MW]
1	Germany	4700
2	Denmark	3300
3	Sweden	8400

4	Finland	5400
5	Poland	500
6	Estonia	2600
7	Lithuania	1000
8	Latvia	1100

b. Load Model

The assumption made for the load model is that the power consumption pattern in 2030 does not vary too much from the 2012's pattern. The load time series data for each price area in 2030 is obtained by scaling the 2012's data to meet the forecasted annual demand for 2030. The hourly time series load data of each country for 2012 is obtained from the ENTSO-E. The results are presented in Table 2.

Table 2. Annual demand of price areas in 2030. Data extracted from [SanNii13].

#	Country	Price Area	Load Demand [GWh]
1	Germany	DE	581000
2	Denmark	DK1	23000
3		DK2	16000
4	Poland	PO	165000
5	Finland	FI	91000
6	Lithuania	LI	11000
7	Latvia	LT	9000
8	Estonia	EE	11000
9	Sweden	SE1	12000
10		SE2	15000
11		SE3	90000
12		SE4	26000

c. Generator Model

The following assumptions were made:

- Transmission capacity within each country is unlimited. This is done by connecting the onshore connection points and the load centres with AC lines with capacity 10000MW each. The cost of the lines is not included in the optimisation.
- The cost of generation is not affected by wind power
- Maximum power generation excluded wind power is as high as the total demand of the respective price area
- Generators other than wind power generators are modelled as power prices in the relevant price areas

The power price data for 2012 is used in this work as initial input. For Sweden, Finland and Estonia, the hourly power price data is taken from the NordPoolSpot (www.nordpoolspot.com). The 2012 hourly price data for Germany is not attainable; therefore the 2010's data obtained from the EEX (www.eex.com) is used and scaled to fit the yearly price of 2012. For Poland, the hourly price data is obtained from PSE (www.pse-operator.pl). For Latvia and Lithuania, their price data on the NordPoolSpot for 2012 is not completed. Therefore, it is assumed that their hourly price is the same as Estonia's. In the next stage, power prices obtained from the WILMAR/Balmorel will be used.

IV. Preliminary Results

The Baltic Sea region is further separated into two regions, denoted as Cases I and II, respectively, as shown in Fig. 4. This is due to the number of nodes NetOp can handle is limited. The wind clusters, onshore substations and in which case study the data are used are presented in Table 3. The wind farms are connected to the closest onshore substations by default as optimisation input. For both cases, the maximum capacities of AC cables, DC cables, and converters are 700MW, 1000MW and 1000MW, respectively.

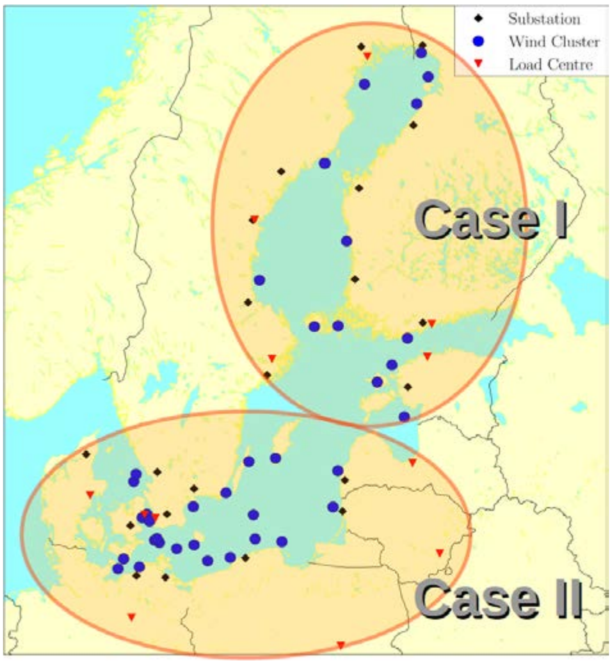

Fig. 4. Case studies.

Table 3. Wind clusters and onshore connection points.

#	Country	Cluster	Capacity [MW]	Latitude	Longitude	Connection Point	Case
1	DE	DE-1	1780	54.8115	14.1094	Lubmin	2
2	DE	DE-2	1800	54.8135	13.7852	Lubmin	2
3	DE	DE-3	1090	54.4579	12.2551	Bentwisch	2
4	DK	DK-1	890	54.5510	11.6587	Bjaerverskov	2
5	DK	DK-2	180	55.6520	12.5810	Bjaerverskov	2
6	DK	DK-3	1980	55.0298	12.9970	Bjaerverskov	2
7	DK	DK-4	160	54.9080	14.7035	Bjaerverskov	2
8	DK	DK-5	150	56.5000	12.0950	Trige	2
9	FI	FI-1	2440	65.6558	24.4852	Isohara	1
10	FI	FI-2	1220	65.2093	24.7811	Isohara	1
11	FI	FI-3	490	64.7023	24.2873	Pyhajoki	1
12	FI	FI-4	620	61.9607	21.2616	Rauma	1
13	FI	FI-5	10	60.1340	20.8890	Rauma	1
14	FI	FI-6	160	59.8590	23.8880	Espoo	1
15	FI	FI-7	500	60.1170	19.9000	Rauma	1
16	SE	SE-1	1420	56.6831	12.1947	Breared	2
17	SE	SE-2	600	55.8781	14.6704	Hemsjo	2
18	SE	SE-3	920	55.0700	13.1030	Hurva	2
19	SE	SE-4	1300	55.5110	12.7790	Hurva	2
20	SE	SE-5	1600	56.1899	16.1460	Hemsjo	2
21	SE	SE-6	550	57.0576	18.0397	Hemsjo	2
22	SE	SE-7	1010	61.1328	17.5281	Stockholm	1
23	SE	SE-8	920	63.5470	20.3350	Sundsvall	1
24	SE	SE-9	60	65.0700	22.0300	Svartbyn	1
25	PO	PO-1	180	54.9914	18.4973	Slupsk	2
26	PO	PO-2	230	55.0601	17.3409	Slupsk	2
27	PO	PO-3	90	54.5461	15.8235	Slupsk	2
28	EE	EE-1	1580	59.2572	23.2171	Lihula	1
29	EE	EE-2	520	58.0541	23.7503	Lihula	1
30	EE	EE-3	500	58.8670	22.5830	Lihula	1
31	LI	LI-1	1000	55.8687	20.6711	Grobina	2
32	LT	LT-1	1100	56.7656	20.8797	Klaipeda	2

a. <u>Case I</u>

The price areas involved in this case study are SE1 – SE3, FI, and EE. The resultant grid topology for this case study is presented in Fig. 5. Some key results from the optimisation are presented in Table 4.

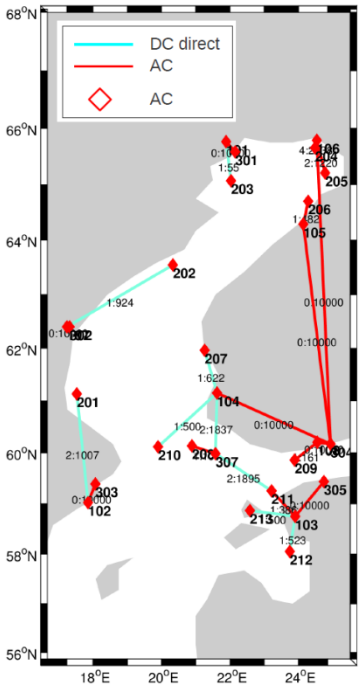

Fig. 5. Resultant grid topology for case I.

Table 4. Key results from Case I.

From node	To node	Branch type	Distance [km]	# of cables	Capacity [MW]	Mean flow [MW] 1 → 2	Mean flow [MW] 1 ← 2
201	102	3	235.7	2	1010	460	0
202	107	3	202.4	1	920	420	0
203	101	3	77.7	1	60	30	0
204	106	1	15.0	4	2440	1100	0
205	106	1	65.5	2	1220	560	0
206	105	1	46.3	1	480	220	0
207	104	3	92.2	1	620	280	0
209	108	1	53.3	1	160	70	0
210	104	3	148.8	1	500	230	0
211	103	1	68.9	1	390	240	40
212	103	3	78.2	1	520	240	0
213	103	3	77.6	1	500	230	0
102	303	1	42.9	0	10000	440	0
107	302	1	3.9	0	10000	400	0
101	301	1	23.4	0	10000	20	0
106	304	1	626.5	0	10000	1650	0
105	304	1	461.1	0	10000	220	0
104	304	1	211.7	0	10000	990	20
108	304	1	21.7	0	10000	70	0
103	305	1	90.2	0	10000	660	10
208	307	1	41.9	1	10	4	0
211	307	3	122.8	2	1900	540	30
307	104	3	130.3	2	1840	520	30

b. <u>Case II</u>

The price areas involved in Case II are SE4, DE, DK1 and DK2, PO, LI, and LT. The resultant grid topology for this case study is presented in Figs. 6 and 7. Some key results from the optimisation are presented in Table 5.

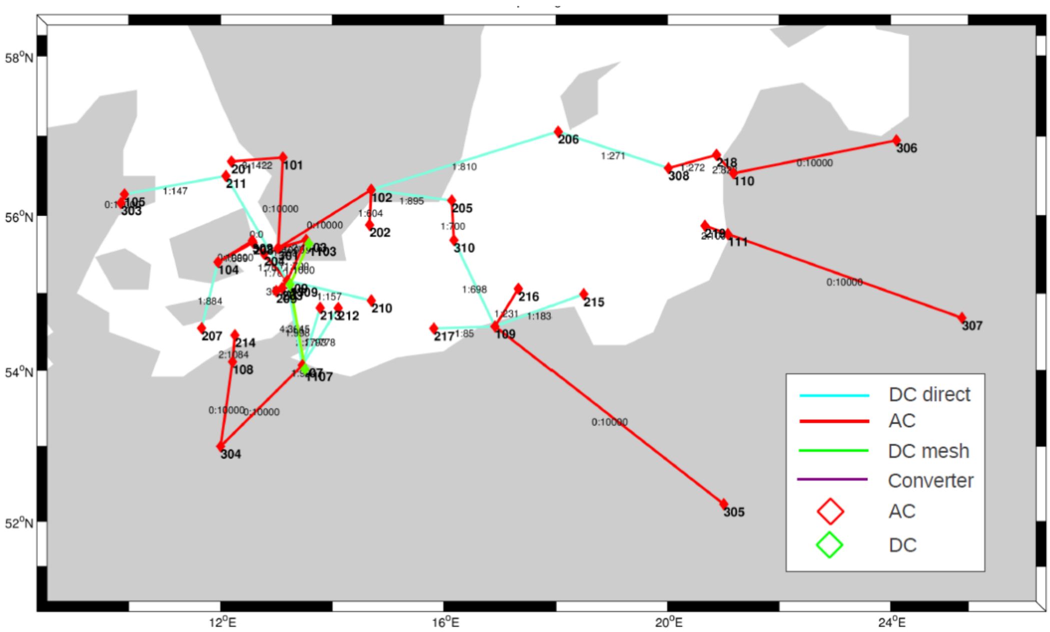

Fig. 6. Resultant grid topology for Case II.

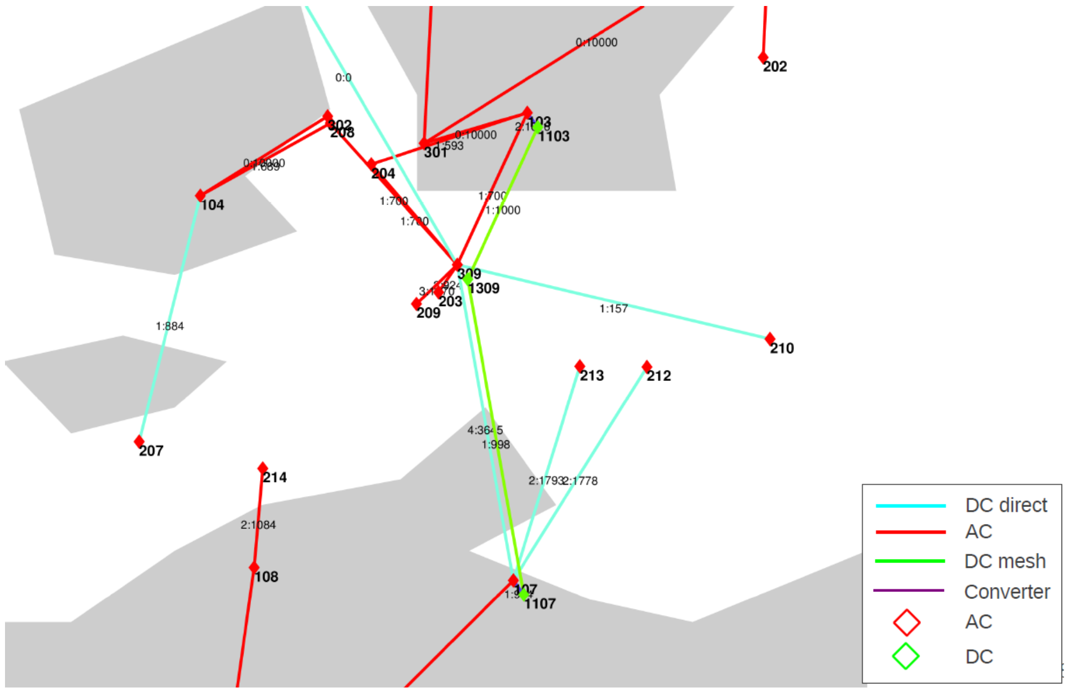

Fig. 7. Connections between DE, SE4 and DK2.

Table 5. Key results from Case II.

From node	To node	Branch type	Distance [km]	# of cables	Capacity [MW]	Mean flow [MW] 1 → 2	Mean flow [MW] 1 ← 2
201	101	1	56.7	3	1420	640	0
202	102	1	49.7	1	600	270	0
204	103	1	51.4	1	590	210	220
205	102	3	90.8	1	900	450	100
206	102	3	220.3	1	810	310	30
207	104	3	96.7	1	890	400	0
208	104	1	48.4	1	690	220	310
211	105	3	115.3	1	150	70	0
212	107	3	92.9	2	1780	800	0
213	107	3	85.7	2	1790	810	0
214	108	1	38.6	2	1080	490	0
215	109	3	111.6	1	180	80	0
216	109	1	60.7	1	230	100	0
217	109	3	71.7	1	90	40	0
218	110	1	31.9	2	830	470	12
219	111	1	28.4	2	1000	450	0
101	301	1	128.2	0	10000	940	300
102	301	1	132.9	0	10000	960	100
103	301	1	33.5	0	10000	150	1490
104	302	1	49.3	0	10000	510	220
105	303	1	13.1	0	10000	60	0
107	304	1	153.4	0	10000	5270	390
108	304	1	124.6	0	10000	820	330
109	305	1	376.6	0	10000	670	100
110	306	1	184.7	0	10000	470	12
111	307	1	293.0	0	10000	450	0
203	309	1	12.1	2	920	420	0
204	309	1	46.7	1	700	620	20
205	310	1	56.3	1	700	470	110
206	308	3	131.1	1	270	70	100
208	309	1	66.7	1	700	350	180
209	309	1	19.7	3	1970	890	0
210	309	3	100.6	1	160	70	0
211	309	3	163.8	0	0	0	0
218	308	1	56.0	1	270	100	70
309	103	1	62.1	1	700	60	540
309	107	3	123.5	4	3650	2680	70
310	109	3	132.5	1	700	480	110
1309	1103	2	62.1	1	1000	70	900
1309	1107	2	123.5	1	1000	900	70
1103	103	4	0	2	1020	60	910
1107	107	4	0	1	1000	900	70

V. Conclusions and Future Works

The grid design work flow has been presented in this work. Some preliminary results on the case studies were also shown, based on some very crude assumptions. In the next stage, CorWind model will be used in place of the model presented in this report.

Then the results obtained will be used to generate the updated power prices for the next design loop, and subsequently the power system analysis will be carried out.

References

[Balmorel01] H.F. Ravn, M. Hindsberger, M. Petersen, R. Schmidt, R. Bøg, P.E. Grohnheit, and H. V. Larsen, J. Munksgaard, J. Ramskov, M.-R. Esop, G. Klavs, A. Galinis, R. Paprocki, M. Wawrzyszczuk and A. Gloukhov (2001). *Balmorel: A model for analyses of the electricity and CHP markets in the Baltic Sea region*. Balmorel Project.

[CutululisNA] N. Cutululis (N.A). *TWENTIES Deliverable 16.1: Offshore wind power data*, unpublished.

[SanNii13] S.Uski-Joutsenvuo and N. Helisto. *Initializing network simulations for case studies of offshore wind power and offshore DC grid integration in the power system of Northern Europe*. 12th Wind Integration Workshop, 22-24 Oct 2013, London, UK.

[Svendsen13] H.G.Svendsen (2013). *Planning tool for clustering and optimised grid connection of offshore wind farms*. Energy Procedia 00, pp. 1 – 13.

[SørensenEA09] P.Sørensen, P. Pinson, N. A. Cutululis, H. Madsen, L. E. Jensen, J. Hjerrild, M. H. Donovan, J. R. Kristoffersen, and A. Vigueras-Rodríguez, (2009). *Power fluctuation from large wind farms – Final report.* Risø DTU.

[NorheimEA05] P. Meibom, R. Barth, I. Norheim, H. Ravn, and P. Sørensen (2006). *Wind power integration in a liberalized electricity market – Final technical report.* Risø National Laboratory.