Design and Optimisation of Offshore Grids in Baltic Sea for Scenario Year 2030

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Offshore Grid Design

Objective

OffshoreDC project [1] WP-5:

- Find an optimal grid structure taking into account:
  - Wind power variations
  - Stochastic power prices
  - On- and offshore load and generation scenarios
- Use formal optimization for a structured approach to finding good grid layouts
  - Huge number of possible grid structures
  - Combinatorial problem solved efficiently by optimization tools
- Results:
  - Which cables to build & capacity on the cables
  - Gives valuable decision support, but:
  - Must be combined with market/network model in an iterative procedure

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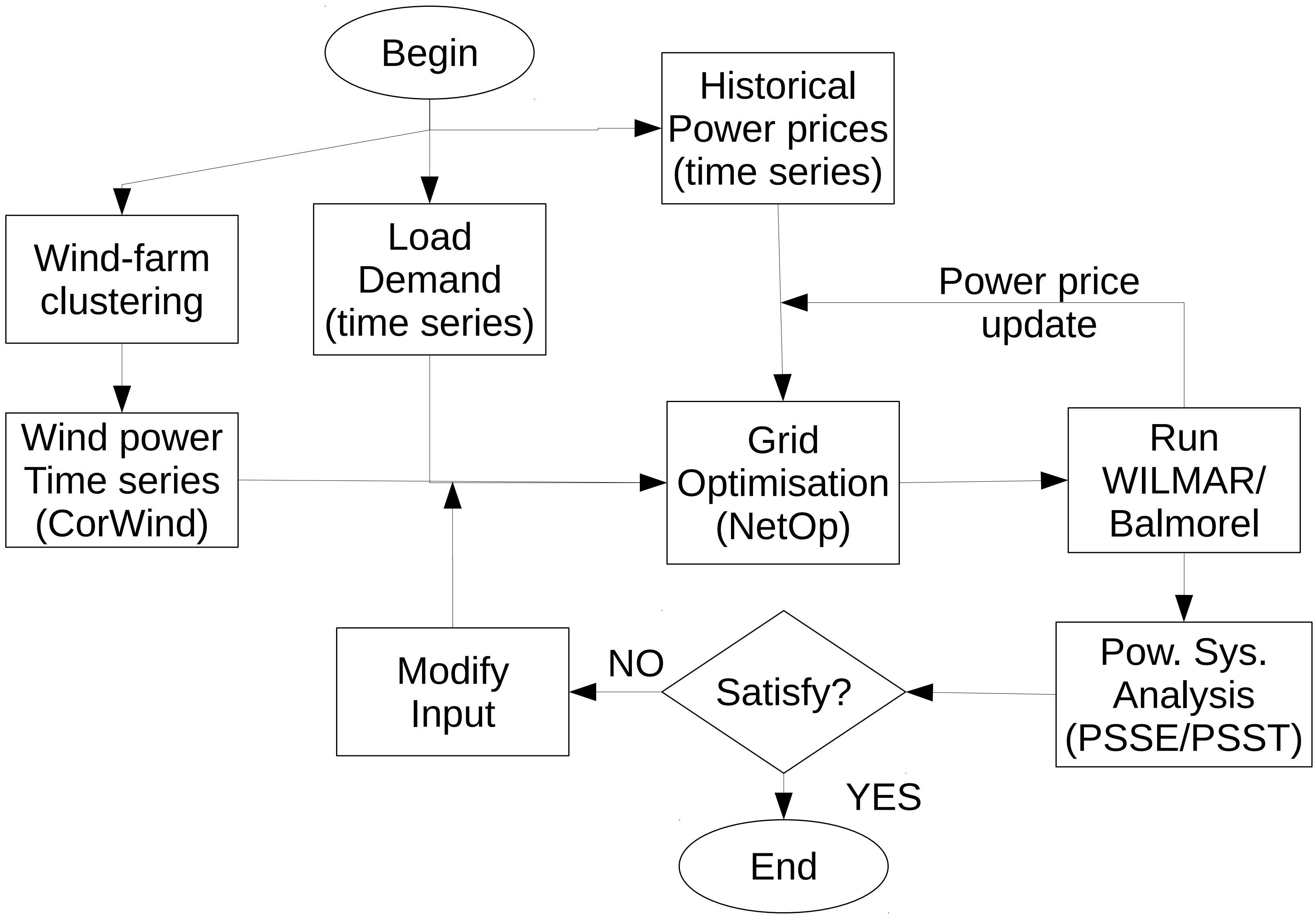
[1] www.offshoredc.dk

Offshore Grid Design

Design Flow Chart



Case Study : Baltic Sea 2030

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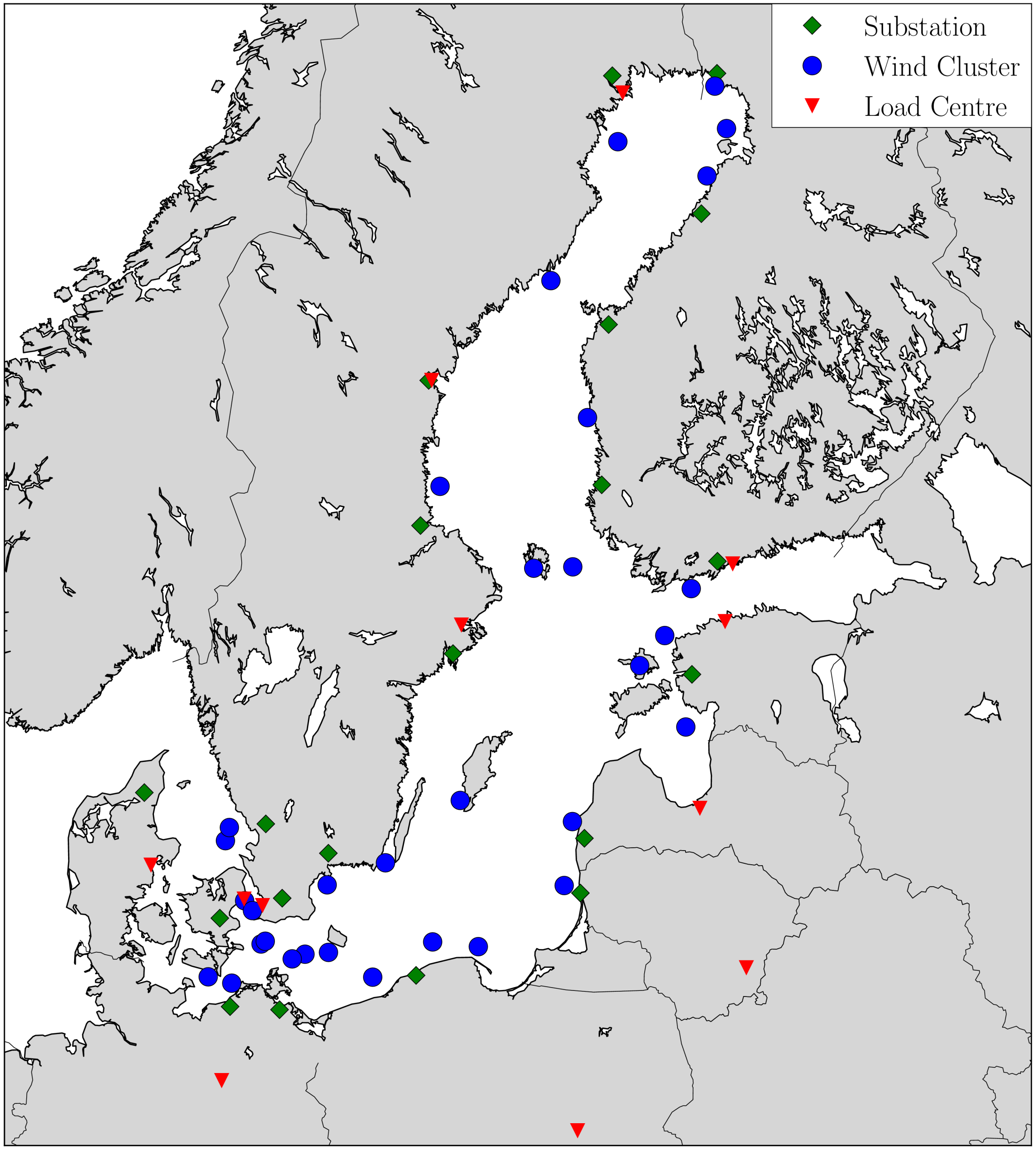

- **Problem :** How to connect the wind farms to the onshore grids?
  - # of offshore windfarms : 97
  - # of onshore substations : 18
  - # of market areas : 12
  - # of combinations = $2^{N(N-1)/2}$
- To reduce the # of combinations:
  - Windfarms owned by the same country
  - Geographical size ± 100km
  - Cluster size ± 2000MW
- Results : Total windfarm clusters = 32

Design Inputs

Objective Function

Network Optimisation Tool : NetOp [1]

- Mixed Integer Linear Programming (MILP Problem)
- Objective function:

$$min\left(C_{Tot}^{branch}+C_{Tot}^{node}+C_{Tot}^{geno}\right)$$

[1] H.G.Svendsen (2013). Planning tool for clustering and optimised grid connection of offshore wind farms. Energy Procedia 35, pp. 297 – 306.

Design Inputs

Wind Power Model

Table 1: Total installed wind power capacity for each country by 2030 [1].

#	Country	Installed Capacity [MW]
1	Germany	4737
2	Denmark	3334
3	Sweden	8413
4	Finland	5433
5	Poland	500
6	Estonia	2602
7	Lithuania	1000
8	Latvia	1100

Assumption: The wind power generation profile is the same across the Baltic sea. **(Not realistic!!)**

Current Model:

- Wind power time series data for wind farms in the Krigersflak area [2].
- Aggregate wind power output of the wind farms and normalise it against the total capacity of the wind farms:

$$W_{profile}(t) = \frac{\sum_{n=i} P_{wf,i}(t)}{\sum_{n=i} P_{wf,i}^{max}}$$

Next step: Use *CorWind* [3] model.

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

[2] H.G.Svendsen (2013). Planning tool for clustering and optimised grid connection of offshore wind farms. Energy Procedia 35, pp. 297 – 306.

[3] P. Sorensen et al., (2009). Power fluctuation from large wind farms – Final report.

Table 2 : Wind clusters and their corresponding onshore connection points. The wind clusters are connected radially to the connection points closest to them as initial *NetOp* input.

#	Country	Cluster Name	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	Bjaerveskov	2
6	DK	DK-3	1980	55.0298	12.9970	Bjaerveskov	2
7	DK	DK-4	160	54.9080	14.7035	Bjaerveskov	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

Table 2 : (continued..)

#	Country	Cluster Name	Capacity [MW]	Latitude	Longitude	Connection Point	Case
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	LV	LV-1	1000	55.8687	20.6711	Grobina	2
32	LT	LT-1	1100	56.7656	20.8797	Klaipeda	2

Design Inputs

Load Model

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Table 3 : Annual demand of each price area in 2030.

#	Price Area	Load Demand [GWh]	Case study
1	DK1	23347	1
2	DK2	15735	1
3	DE	581128	1
4	PO	165344	1
5	FI	90922	2
6	LI	10922	1
7	LT	8699	1
8	EE	10921	1
9	SE1	12461	2
10	SE2	14631	2
11	SE3	90392	2
12	SE4	25693	1

$$L_{p.area}^{2030} = L_{p.area}^{2012} \times \frac{L_{country}^{2030}}{L_{country}^{2012}}$$

Note:

$L_{p.area}^{2012}$, $L_{country}^{2012}$ Extracted from time series data from *ENTSO-E*

$L_{country}^{2030}$ Forecast data from [1]

Assumption: The load consumption pattern of each price area does not vary too much from 2012's pattern.

[1] 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.

Design Inputs

Generator Model

- Generators other than wind power generators are modelled as power prices in the relevant price areas.

Assumptions:

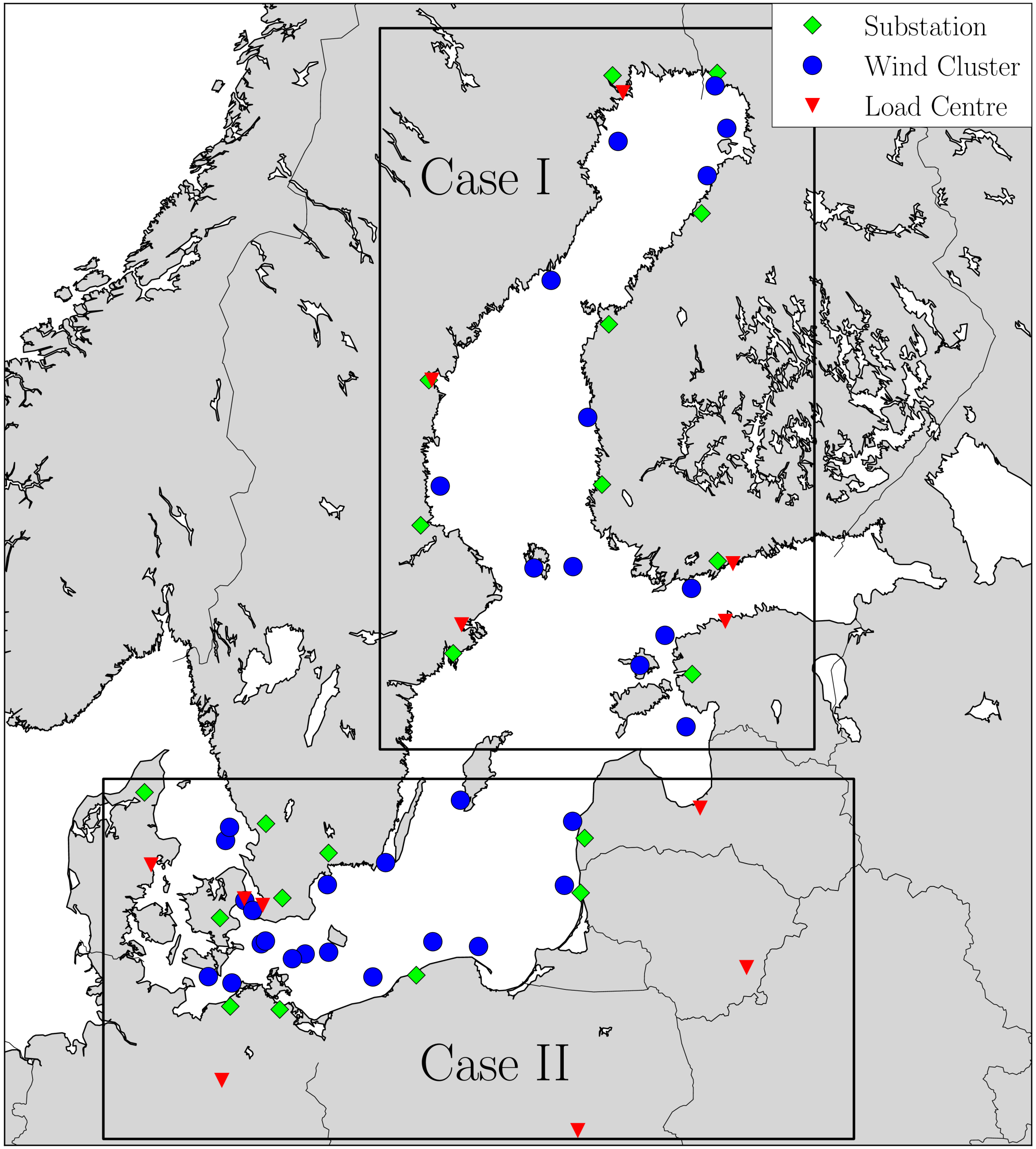
- Transmission capacity within each country is unlimited.
- Cost of generation is not affected by wind power.
- Maximum power generation (exclude wind) is as high as the total demand of the respective price area.

Power prices :

- 2012 time series data is used.
- Sweden, Finland, & Estonia (www.nordpoolspot.com)
- Germany (www.eex.com)
- Poland (www.pse-operator.pl)
- Latvia & Lithuania (assume the same as Estonia's)

Preliminary Results

Case Studies



Preliminary Results

Case I

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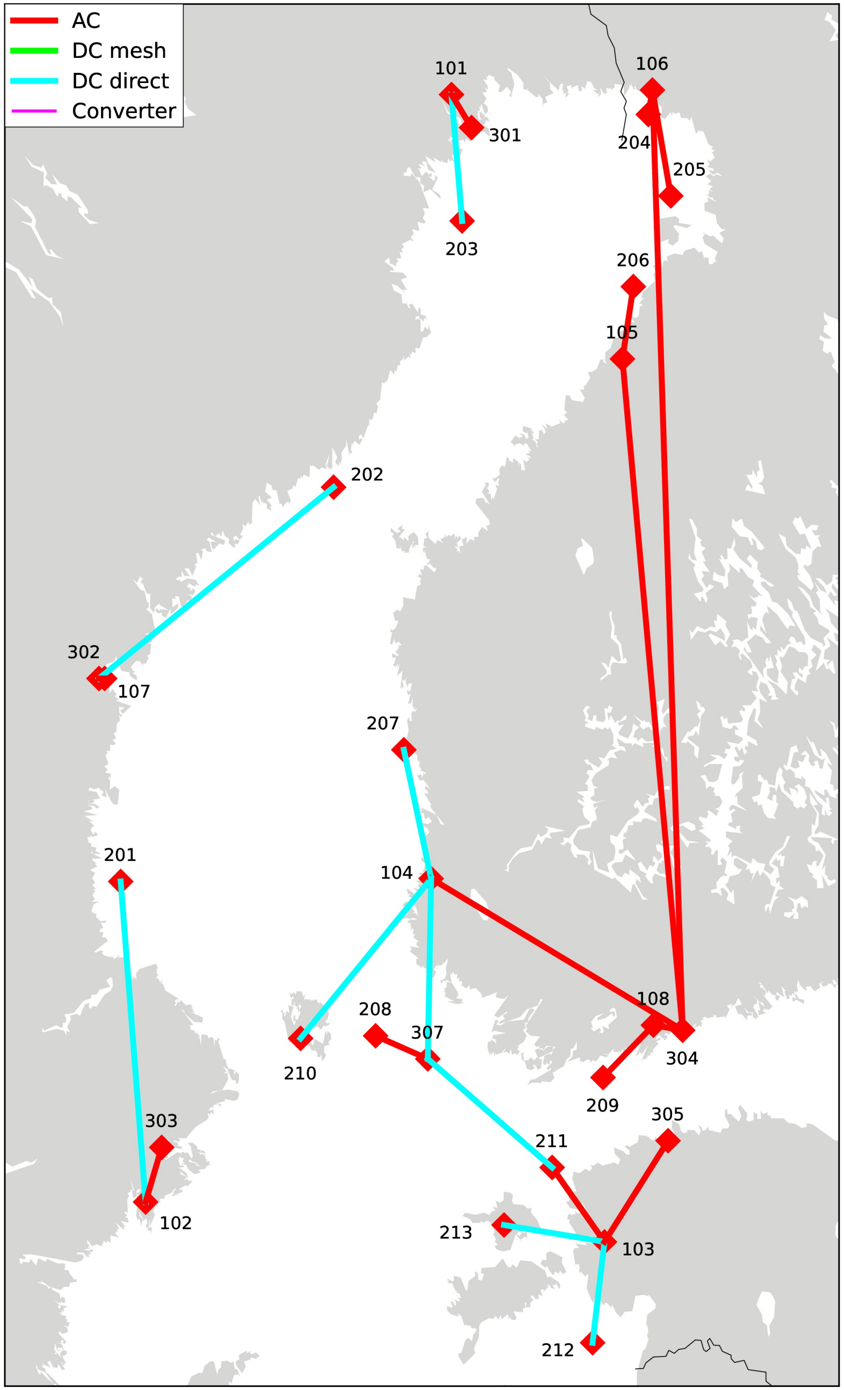
- SE1 – SE3 :
  - WFs – substations:
    - Radial Connections
    - Direct DC > 70 km
- Northern FI:
  - WFs – substations:
    - AC lines ≤ 70 km
- Southern FI & EE:
  - Offshore connection point 307 collects power from WFs 208 (1580 MW capacity) & 211 (10 MW capacity).
  - Most power flows to FI. Mean flows:
    - 211 → 307 : 540 MW
    - 208 → 307 : 4 MW
    - 307 → 104 : 520 MW
- Wind power in EE (103 → 305):
  - Total 660 MW from WFs 211, 212 and 213.



Preliminary Results

Case I

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Table 4 : Key results for case I.

from node 3	to node	Branch type	Distance (km)	# of cables	Capacity (MW)	mean flow (MW) 1 → 2	mean flow (MW) 1 ← 2
201	102	3	236	2	1010	460	0
202	107	3	202	1	920	420	0
203	101	3	78	1	60	30	0
204	106	1	15	4	2440	1100	0
205	106	1	66	2	1220	560	0
206	105	1	46	1	480	220	0
207	104	3	92	1	620	280	0
209	108	1	53	1	160	70	0
210	104	3	149	1	500	230	0
211	103	1	69	1	390	240	40
212	103	3	78	1	520	240	0
213	103	3	78	1	500	230	0
102	303	1	43	0	10000	440	0

Branch type: 1 = AC, 2 = DC mesh, 3 = DC direct, 4 = Converter

Preliminary Results

Case I

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Table 4 : (continued.)

from node	to node	Branch type	Distance (km)	# of cables	Capacity (MW)	mean flow (MW) 1 → 2	mean flow (MW) 1 ← 2
107	302	1	4	0	10000	400	0
101	301	1	23	0	10000	20	0
106	304	1	627	0	10000	1650	0
105	304	1	461	0	10000	220	0
104	304	1	212	0	10000	990	20
108	304	1	22	0	10000	70	0
103	305	1	90	0	10000	660	10
208	307	1	42	1	10	4	0
211	307	3	123	2	1900	540	30
307	104	3	130	2	1840	520	30

Note: Node 307 is the offshore node suggested by NetOp.

Preliminary Results

Case II

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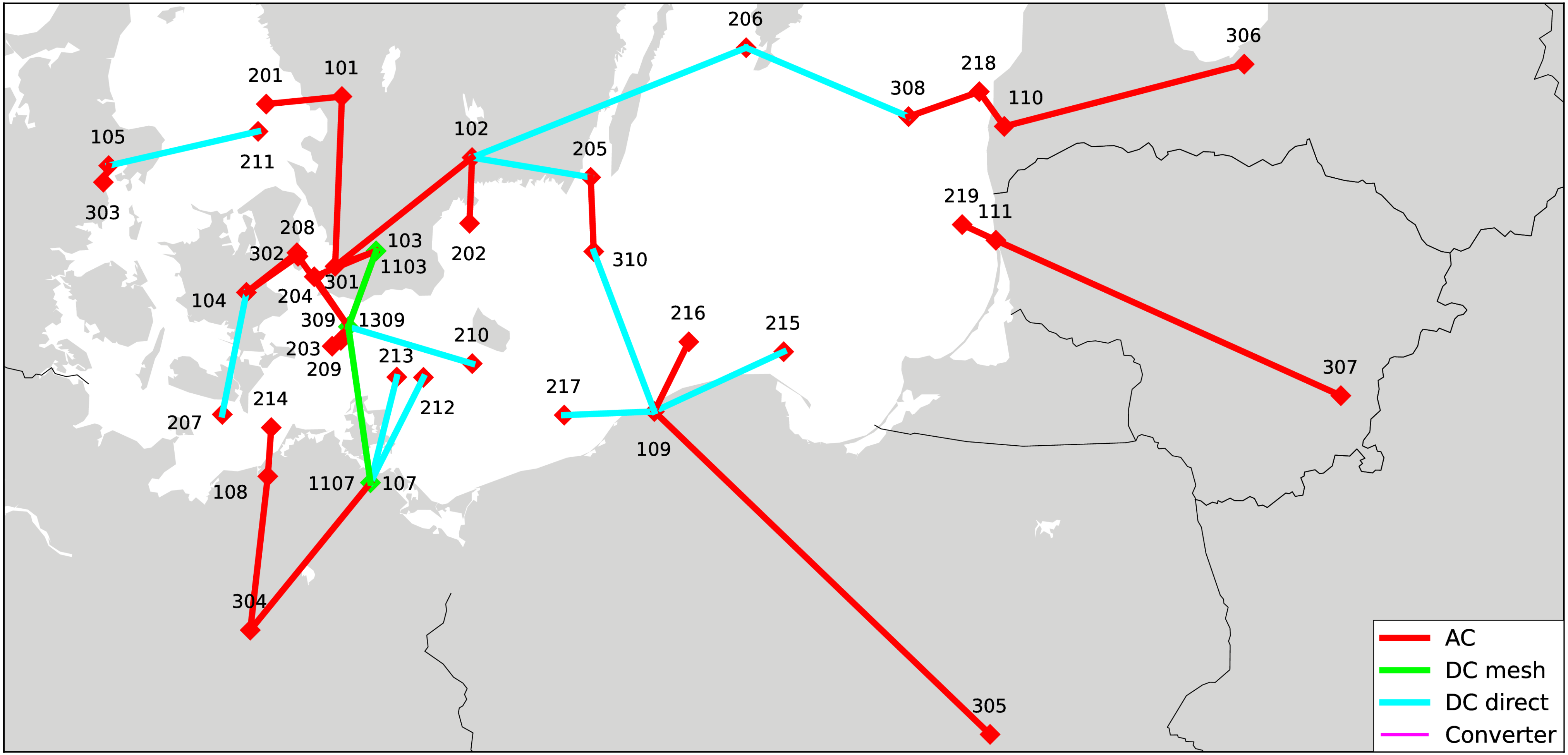
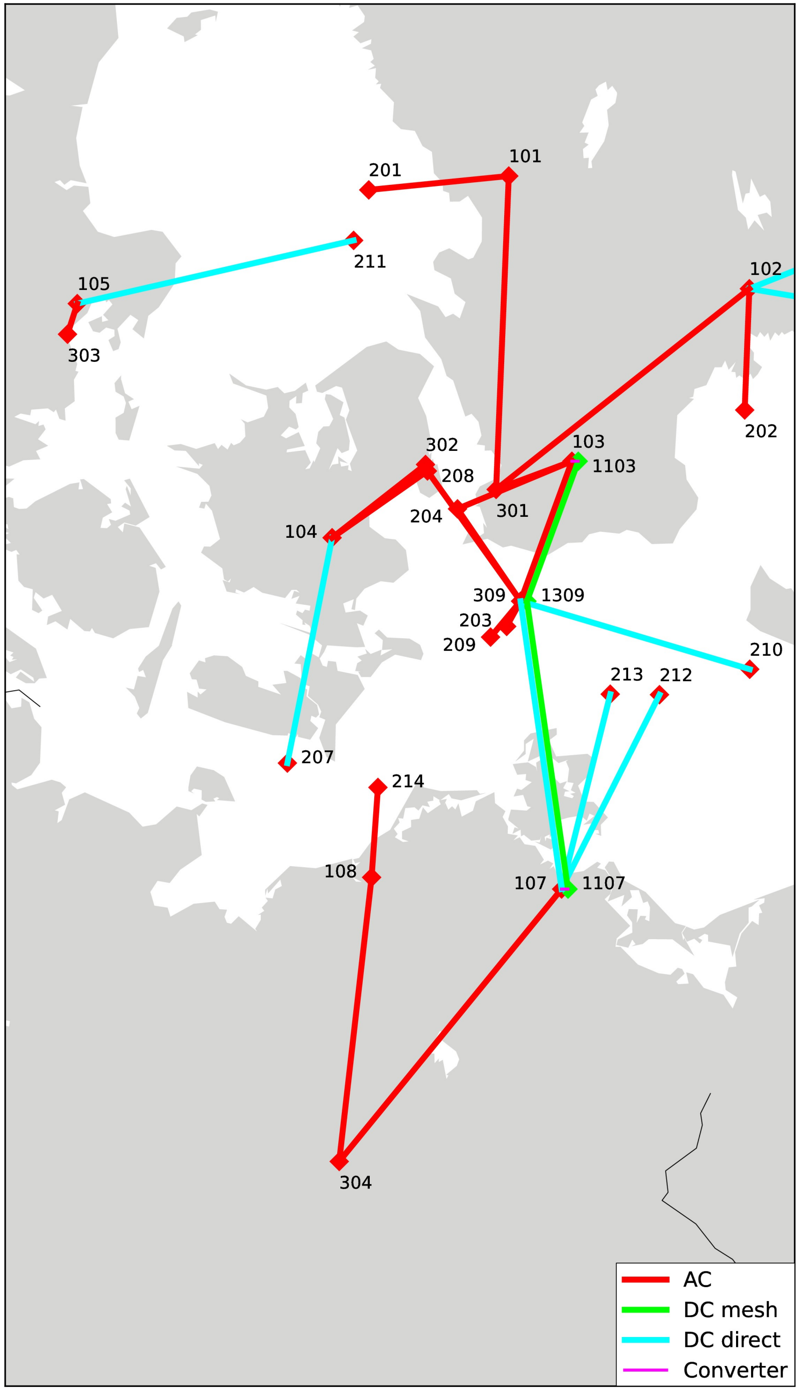


Preliminary Results

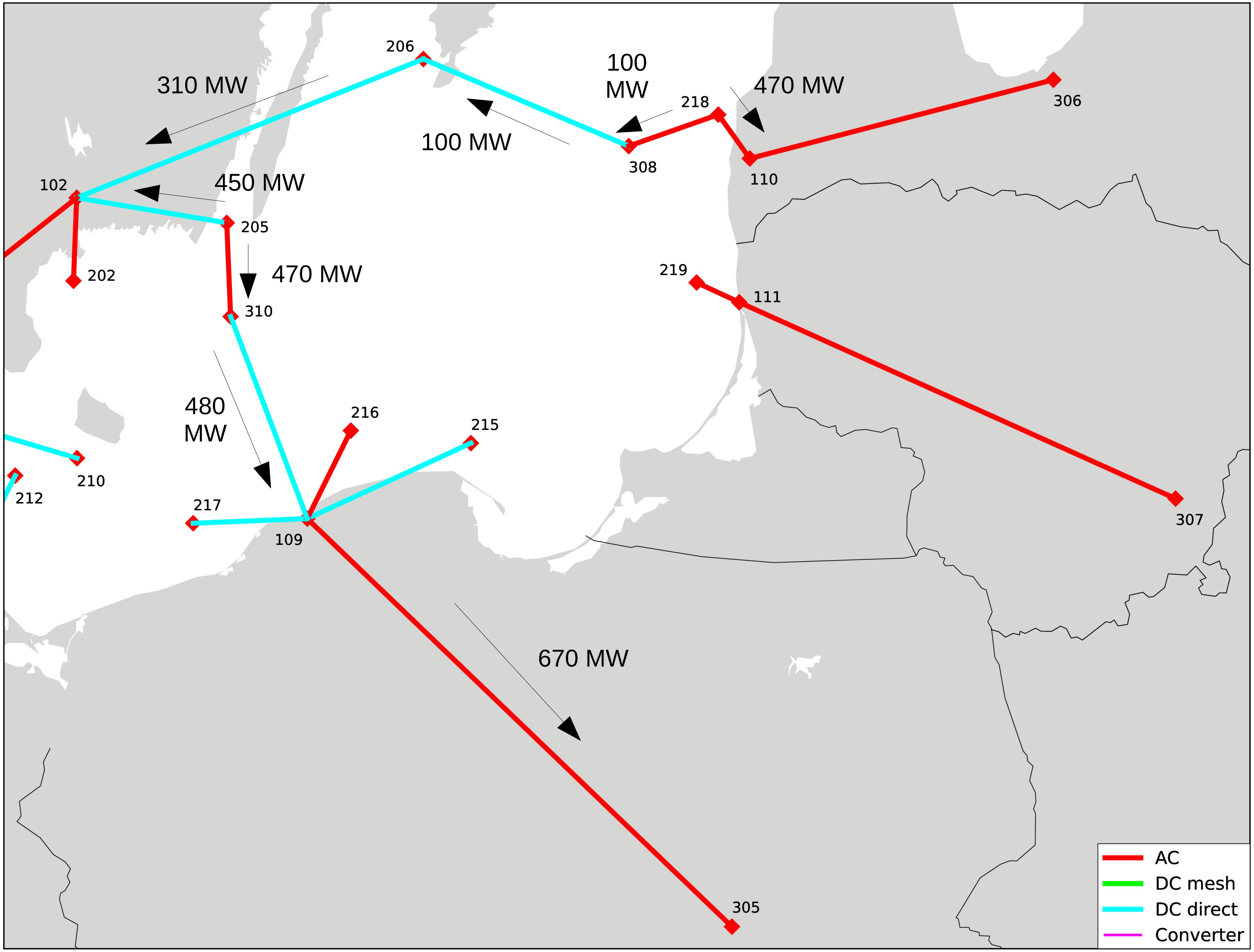
Case I

- SE4, DK1 and DE are connected at point 309.
- 103 → 309 (AC cable): 540 MW mean flow
- Wind power from WFs 203, 204, 208, 209 and 210 are collected at offshore node 309.
- 309 → 107 (4 DC cables): 2680 MW
- 3-terminal HVDC connects 103, 309, 107. Power transfer 900 MW from 103 to 107.



Preliminary Results

Case II



Preliminary Results

Case II

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Table 5 : Key results for 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	57	3	1422	640	0
202	102	1	50	1	604	270	0
204	103	1	51	1	593	210	220
205	102	3	91	1	895	450	100
206	102	3	220	1	810	310	30
207	104	3	97	1	884	400	0
208	104	1	48	1	689	220	310
211	105	3	115	1	147	70	0
212	107	3	93	2	1778	800	0
213	107	3	86	2	1793	810	0
214	108	1	39	2	1084	490	0
215	109	3	112	1	183	80	0
216	109	1	61	1	231	100	0

Branch type: 1 = AC, 2 = DC mesh, 3 = DC direct, 4 = Converter

Preliminary Results

Case I

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Table 5 : (continued.)

from node	to node	Branch type	Distance (km)	# of cables	Capacity (MW)	mean flow (MW) 1 → 2	mean flow (MW) 1 ← 2
217	109	3	72	1	90	40	0
218	110	1	32	2	830	470	12
219	111	1	28	2	1000	450	0
101	301	1	128	0	10000	940	300
102	301	1	133	0	10000	960	100
103	301	1	34	0	10000	150	1490
104	302	1	49	0	10000	510	220
105	303	1	13	0	10000	60	0
107	304	1	153	0	10000	5270	390
108	304	1	125	0	10000	820	330
109	305	1	377	0	10000	670	100
110	306	1	185	0	10000	470	12
111	307	1	293	0	10000	450	0

Branch type: 1 = AC, 2 = DC mesh, 3 = DC direct, 4 = Converter

Preliminary Results

Case II

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Table 5 : (continued.)

from node	to node	Branch type	Distance (km)	# of cables	Capacity (MW)	mean flow (MW) 1 → 2	mean flow (MW) 1 ← 2
203	309	1	12	2	920	420	0
204	309	1	47	1	700	620	20
205	310	1	56	1	700	470	110
206	308	3	131	1	270	70	100
208	309	1	67	1	700	350	180
209	309	1	20	3	1970	890	0
210	309	3	101	1	160	70	0
218	308	1	56	1	270	100	70
309	103	1	62	1	700	60	540
309	107	3	124	4	3650	2680	70
310	109	3	133	1	700	480	110

Note : 308 – 310 are offshore nodes resulted from the optimisation.

Branch type: 1 = AC, 2 = DC mesh, 3 = DC direct, 4 = Converter

Preliminary Results

Case II

Table 5 : (continued.)

from node	to node	Branch type	Distance (km)	# of cables	Capacity (MW)	mean flow (MW) 1 → 2	mean flow (MW) 1 ← 2
1309	1103	2	62	1	1000	70	900
1309	1107	2	124	1	1000	900	70
1103	103	4	0.0	2	1020	60	910
1107	107	4	0.0	1	1000	900	70

Branch type: 1 = AC, 2 = DC mesh, 3 = DC direct, 4 = Converter

Future Work

- Re-run the cases I & II with *CorWind* models.
- “Close the loop”:
  - Evaluate the technical feasibility of the grids
  - Investigate the how the grids will impact on the power market

Thanks!!