North Sea Offshore Grid Development: Combined Optimization of Grid and Generation Investments Towards 2050

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***Abstract*—The North Sea region offers large amounts of investable offshore wind generation. In addition, several transmission lines are located in the area. This paper models optimal transmission and generation investments in scenarios towards 2050 in the North Sea region. A meshed scenario is developed to investigate the viability of connecting future transmission and offshore wind generation investments. A radial scenario is also developed and compared to the meshed scenario. It is shown that going towards a meshed solution can increase the offshore wind investments by several GWs, with Germany seeing the biggest difference between the radial and meshed scenarios.**

Keywords-Grid; Interconnector; Meshed; North Sea; Offshore; Optimization; Transmission; VRE, Wind

I. INTRODUCTION

The North Sea region has already significant offshore wind generation, and it offers large amounts of investable generation with high capacity factors (CFs) in the future. In addition to offshore wind, several transmission lines are located in the area. This paper models optimal transmission and generation investments in scenarios towards 2050, and investigates the viability of connecting future transmission and offshore wind generation investments via hubs to create an offshore grid.

Two scenarios are modelled and compared in this paper, with focus on the North Sea region. A radial scenario is created using the traditional solution of connecting offshore wind power plants (OWPPs) directly to shore and using country-to-country lines for transmission. The meshed case enables an integrated approach of combining offshore wind generation and transmission. The modelling is carried out using the Balmorel energy system model [1].

The benefits of a meshed North Sea offshore grid have been shown in previous research, e.g., [2], [3]. In many studies, the generation investments have been treated as fixed exogenous parameters. This paper contributes to the literature by allowing both generation and transmission investments to be optimized by Balmorel, i.e., to be treated endogenously, as recommended in [4]. In addition, scenario years 2030 and 2050 are optimized concurrently, which allows optimal investments in 2030 considering planned investments in the future.

To compare offshore wind to other renewables, onshore wind and solar photovoltaic (PV) investments are also optimized. Other generation types are also part of the optimization, but only small amounts of gas turbine investments are seen necessary as back-up capacity.

DTU Wind Energy's CorRES tool [5] is used to simulate the variable renewable energy (VRE) time series used in Balmorel. CorRES models the varying wind and solar PV CFs depending on installation locations, and the spatiotemporal dependencies in VRE generation. Especially offshore wind is modelled in detail, starting from the planned locations of individual OWPPs.

All analysed scenarios show significant transmission investments, with increased connection of Norwegian hydropower to the other countries. The results indicate that going to a meshed solution can increase the total offshore wind investments by several GWs. In addition to offshore wind, the scenarios include large amounts of onshore wind and solar PV. Radial transmission lines provide a large share of country-to-country transmission capacity also in the meshed case; however, the analyses show that integrating the offshore hubs as part of the transmission system can be beneficial.

II. SCENARIOS

This section describes the scenarios analysed in this paper. The modelled countries are presented, and the European-wide energy system scenario used as the background for the scenarios is described. Finally, the grid structures of the radial and meshed scenarios are presented.

A. Modelled countries

The scenario modelling focuses on the North Sea region; the countries with investment optimisation are Denmark (DK), Norway (NO), Germany (DE), UK, Netherlands (NL)

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and Belgium (BE). For UK, the energy system of Great Britain (GB) is modelled, so the numbers refer to GB.

Some of the modelled countries are split to regions, as show in Figure 1, to model important intra-country transmission investments. Surrounding countries participate in the electricity dispatch optimisation, and follow an exogenous generation and transmission capacity development as described in the next subsection.

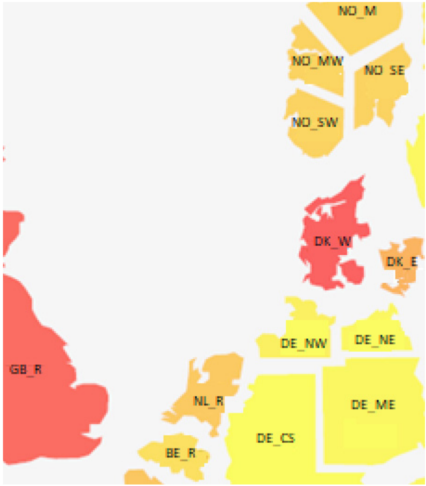

Figure 1. Regional split of the countries with investment optimization. NO_N, located in the northern Norway, is not visible on the map.

B. European-wide background scenario

The scenarios presented in this paper are aligned with the European-wide Nordic Energy Technology Perspectives (NETP) 2016 scenario [6] in different ways. First, the electricity consumption development until 2050 is taken from NETP 2016. In addition, assumed fuel and emission price development follows NETP 2016.

For the countries with investment optimization (see Figure 1), generation and transmission investments are optimized for the scenarios studied in this paper. However, the generation and transmission development of the surrounding countries is taken from NETP 2016 until 2050.

C. Radial and meshed scenarios

The radial and meshed scenarios are differentiated by the allowed grid structures in the investment optimization. In the radial scenario, only radial country-to-country transmission lines are possible, and OWPPs can be connected only radially to a single country, as shown in Figure 2; the possible future OWPPs are taken from [7], with some modifications. The different types (nearshore, HVAC connected offshore and HVDC connected offshore) are assigned looking at distance to shore, distance to grid connection point and project size. While such analysis sets the investable GWs of different OWPP types in different regions, Balmorel investment optimization decides how much of these potentials are invested in.

In the meshed scenario, OWPPs can be connected to hubs, and the hubs can be utilised as a part of the transmission infrastructure. The investable hub-connected offshore wind GWs are shown in Figure 3. In addition, the meshed scenario includes all the radial country-to-country connections available in the radial scenario; thus, the meshed solution is not forced on the system, but appears only if it is favourable in the investment optimization.

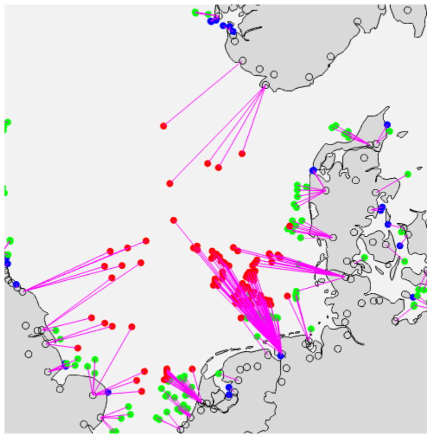

Figure 2. OWPPs used to estimate investable offshore wind capacities in the radial scenario: blue denotes nearshore, green HVAC connected offshore and red HVDC connected offshore OWPPs.

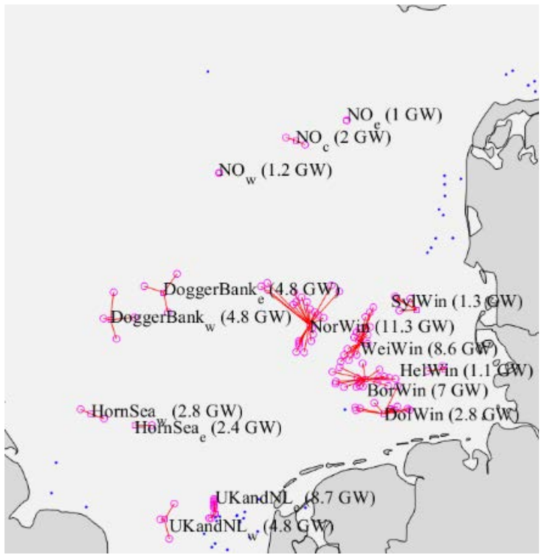

Figure 3. Investable hub-connected offshore wind capacities in the meshed scenario. The OWPPs connected to UKandNLw are British, and the ones connected to UKandNLe are Dutch. DoggerBank and HornSea consist of British OWPPs, and all hubs ending in “Win” consist of German OWPPs.

III. MODELLING

This section describes the VRE time series simulation methodology used. It then proceeds to present the Balmorel investment optimisation. In addition, important cost assumptions towards 2050 are presented.

A. VRE time series simulation

The CorRES tool [5] is used to generate the VRE time series. Its applicability to large-scale VRE simulations, based on meteorological reanalysis data, has been presented, e.g., in [8]. Using reanalysis wind speeds directly can cause erroneous CFs in simulations [8], [9]. To remedy this, historical CF data were used to calibrate wind speeds in CorRES, using an approach similar to [9]; WRF wind speeds were scaled to match historical CFs estimated from publically available sources.

For CorRES simulations for the future scenarios, technical wind power plant (WPP) parameters are required. In this study, the expected hub height development was taken from [10]; with onshore wind going towards 110 m and offshore wind towards 140 m by 2050. In addition, specific power is assumed to decrease. Example of the general development of offshore wind CFs can be seen in Table I. When going further from the shore (from nearshore towards hub-connected OWPPs), the CF increases, and investments in 2050 are expected to have higher CFs than investments in similar locations in 2030.

In addition to modelling CFs, CorRES models the spatiotemporal dependencies in VRE generation. An example of the spatial dependencies can be found in Figure 4; it can be seen that in analysis covering a large geographical area, the modelling of spatial dependencies is important. E.g., wind investments in NO have different spatial correlation in relation to German wind power compared to investment in DK, which can make a difference when all countries take part in the same energy market and electricity price formation.

TABLE I. AVERAGE OFFSHORE WIND CAPACITY FACTORS

Type	If invested in 2030	If invested in 2050
Nearshore	0.46	0.50
Offshore (HVAC)	0.51	0.54
Offshore (HVDC)	0.53	0.55
Hub-connected	0.54	0.57

The CFs are averages of all regions in the meshed scenario (radial scenario does not have hub-connected offshore wind).

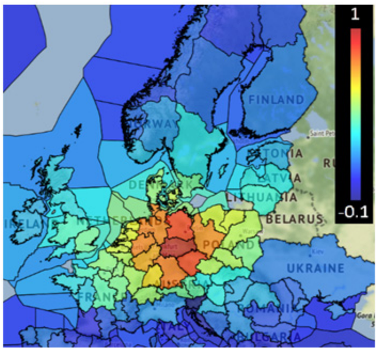

Figure 4. Spatial correlations in wind generation looking from an example German onshore region (based on 35 years of simulated hourly data).

B. *Investment optimisation*

Balmorel is a cost minimization tool coded in the GAMS language [1]. From the different optimization modes of Balmorel, BB4 has been utilized in this paper. BB4 implements intertemporal value maximization [1], where the value of a future year with respect to the first year depends on the discount rate assumption. Under the assumption of a comparatively low discount rate (3.25% is used in this paper), this gives rise to solutions that are expected to be closer to a social optimum compared to myopic optimization, i.e., optimizing without considering what is expected to occur in the future. An example of intertemporal optimization is the consideration of transmission investment in earlier years to be ready to connect future generation investments.

Due to computation time, a full year of hourly data cannot be used in the investment optimization. In this paper, 4 weeks were selected (one for winter, summer, spring and autumn, with hourly resolution) to represent the load and generation behaviour; the time series are scaled so that annual consumption and generation TWhs are respected.

Although the base version of Balmorel is linear, mixed integer programming (MIP) can be used to model fixed costs. This is especially important in HVDC components, as will be described in the next subsection. As MIP is computationally expensive, it is used only for the HVDC components related to transmission (country-to-country offshore lines and all offshore meshed grid components).

C. *Cost assumptions*

The most important cost parameters updated compared to the background NETP 2016 scenario [6] are VRE generation and HVDC component costs. In addition, as NETP 2016 includes only a radial grid structure, all costs related to the meshed grid are modelled.

VRE generation cost development until 2050 is taken from [10] (as it was available in June 2017); some of the most important investment costs are shown in Table II. It can be seen that all VRE types are expected to get cheaper, but with different rates. Solar PV is expected to experience more than 50% investment cost reduction already by 2030 (compared to 2015). Offshore wind is getting cheaper faster than onshore wind, but remains more expensive per MW until 2050.

VRE grid connection costs are calculated differently depending on the generation type. For onshore wind and solar PV, the costs are taken directly from [10]. For HVAC connected offshore wind, distance to grid connection point is calculated for each potential future OWPP and the per km cost from [10] is used to estimate grid connection costs per region for Balmorel. For HVDC connected offshore wind, the HVDC cost parameters presented in the next paragraph are used. For hub-connected offshore wind, it is assumed that connection until hub is HVAC; the hub and lines thereafter are treated as described in the next paragraph.

The HVDC cost model and required parameters are taken from [11] (the average cost parameter set is used). They are applied to HVDC connected OWPPs, to offshore country-to-country transmission lines and to all components related to the meshed offshore grid (hubs and lines). As [11] gives only current cost numbers, the future cost reduction assumed in [10] for OWPP grid connection was applied also for the HVDC cost parameter to get the 2030 and 2050 numbers.

An example of applying the HVDC cost model to estimate component costs can be seen in Table III, where offshore hub costs are estimated for different hub sizes. The M€/MW cost increases about the same when going from 2 GW to 1 GW (Δ = 1 GW) than when going from 1 GW to 0.7 GW (Δ = 0.3 GW). This shows that very small hubs do not seem economically feasible; in Balmorel, the MIP modelling is used to take this into account.

TABLE II. VRE GENERATION INVESTMENT COSTS

VRE type	Today (2015)	2030	2050
Onshore wind (M€/MW)	1.02	0.86	0.79
Offshore wind (M€/MW)	2.46	1.64	1.39
Nearshore wind (M€/MW)	2.21	1.50	1.28
Solar PV (M€/MWp)	1.07	0.50	0.39

All costs in €2015. The wind investment costs exclude grid connection costs.

TABLE III. HUB INVESTMENT COSTS IN THE MESHED SCENARIO

Hub size (GW)	2030 (M€/MW)	2050 (M€/MW)
2	0.19	0.17
1	0.22	0.20
0.7	0.25	0.22

All costs in €2015. These costs include only the hub; in addition to building a hub (platform), OWPPs need to be invested in to get generation from the hub.

IV. RESULTS

This section presents the radial and meshed scenarios resulting from the Balmorel optimization. Transmission and VRE generation investments area shown, with a look at 2030 and the accumulated investments by 2050. The section begins with a look at the assumed exogenous transmission development (the starting point for both the radial and meshed scenario).

A. Exogenous transmission capacities

The expected exogenous transmission development is shown in Figure 5. For example, the 1.4 GW Viking Link between DK and UK is assumed to be developed exogenously, and the transmission capacity between DE_{NW} and DE_{CS} is expected to increase to 17.6 GW (this assumption comes from [6]).

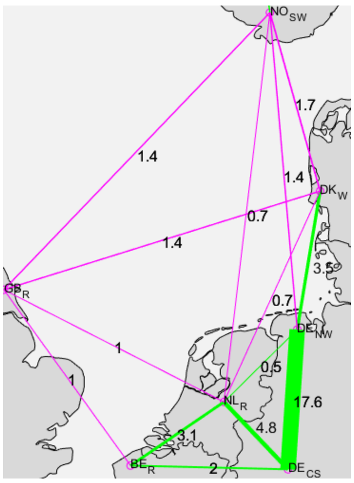

Figure 5. Assumed exogenous transmission development in the North Sea region (GW). Capacities, not actual locations of the lines, are illustrated. On-land lines are in green and offshore HVDC lines in magenta (DK_w to DE_{NW} is on-land, even though it appears offshore in the figure).

B. The radial scenario: transmission expansion

The endogenous transmission investments in the radial scenario are shown in Figure 6 (the investments are in addition to the exogenous development shown in Figure 5). It can be seen that the connections from NO to the other countries are strengthened significantly, mostly to combine the flexible Norwegian hydropower to the increasing VRE generation shares in all countries. This is in line with the results shown, e.g., in [2]. Significant transmission capacity development is also seen between DE and GB via BE.

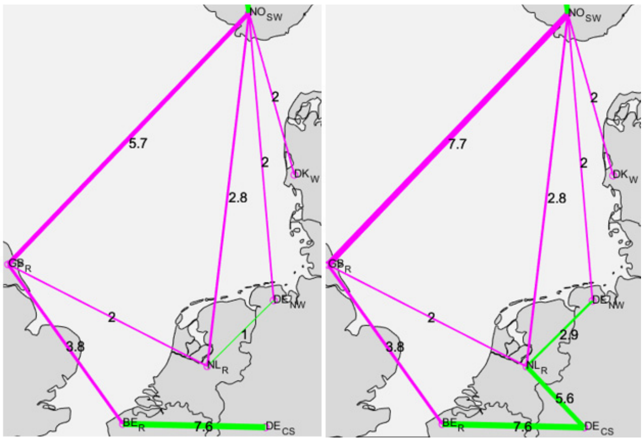

Figure 6. Endogenous transmission investments in 2030 on the left and accumulated investments by 2050 on the right for the radial scenario (GW). On-land lines are in green and offshore lines in magenta.

C. Preliminary results of the meshed scenario

The endogenous transmission investments in the meshed scenario are shown in Figure 7. It can be seen that only German hubs are built in the meshed scenario in 2030. By 2050, also British hubs are built.

Figure 7 shows that the connection from NO to GB is very similar in the meshed scenario compared to the radial scenario. However, the increased connections from NO and from GB to continental Europe are provided by both radial lines and by utilising transmission via the hubs in the meshed scenario.

The capability of Balmorel to carry out intertemporal optimisation affects the transmission results shown in Figure 7. Some lines, such as the connection between NL and UK, are built already in 2030, waiting for hub-connected offshore investments in 2050.

It needs to be noted that all results relating to the meshed scenario are preliminary, since due to time restrictions the optimisation was carried out with less precision than the radial scenario. The meshed scenario is significantly slower to optimise because of the large number of cost components that require MIP modelling (hubs and lines). Full optimisation of the meshed scenario is underway.

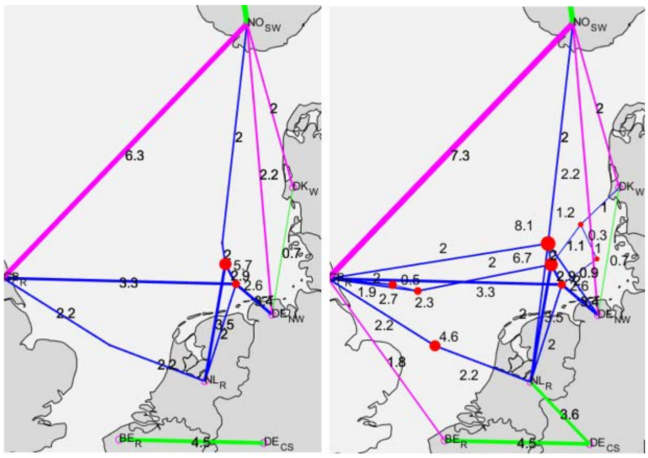

Figure 7. Endogenous transmission and hub investments in 2030 on the left and accumulated investments by 2050 on the right for the meshed scenario (GW). Radial offshore lines are in magenta, lines related to the meshed grid in blue, on-land lines in green, and hubs in red.

D. Installed VRE generation

An overview of the installed wind generation capacities in the scenarios are shown in Table IV. It can be seen that by 2030 the wind installations are about the same in both scenarios (the slightly lower offshore capacity in the meshed scenario is explained by higher CFs of hub-connected OWPPs). However, by 2050 the meshed scenario shows 5 GW higher offshore wind than the radial case; respectively, onshore wind capacity is lower.

As shown in Table IV, in 2030 around 10 % of offshore wind capacity is expected to be hub-connected in the meshed scenario (all in Germany). By 2050, the share increases to more than one fourth (with also British hubs).

Solar PV installations are about the same in both scenarios, rising to around 225 GW by 2050. Even though in GW this is approximately as much as the total wind installations, the solar PV CFs are around 0.1, whereas the offshore wind CFs are around 0.5 and the onshore wind CFs around 0.3. Thus, wind energy generation is much higher than solar PV generation in both scenarios.

DE is the country with most significant differences between the radial and meshed scenarios. As Table V shows, the radial scenario shows 16 GW of offshore wind by 2050, whereas the meshed scenario shows 35 GW. Onshore wind capacity is very similar in the radial and meshed scenario. Even though DE is expected to be a significant electricity importer in both scenarios by 2050 (with the decommissioning of both nuclear and fossil generation), in the meshed scenario the imports are less than in the radial scenario due to more offshore wind.

DE importing less in the meshed scenario than in the radial scenario affects other countries. For example, offshore wind capacity in NL by 2050 is 25 GW in the radial scenario but 16 GW in the meshed scenario. This decreases the amount of electricity exported from NL in the meshed scenario compared to the radial one.

For GB, the amount of offshore wind capacity is approximately the same in the radial and meshed scenarios: 43 GW and 44 GW by 2050, respectively. Thus, in all scenarios GB is expected to have the largest amount of offshore wind of all the analysed countries. In the meshed scenario, 23 % of the offshore wind capacity in GB is expected to be hub-connected by 2050.

TABLE IV. WIND GENERATION INSTALLATIONS IN THE SCENARIOS

	Offshore wind (GW)			Onshore wind (GW)		
Scenario	**Starting point**	**2030**	**2050**	**Starting point**	**2030**	**2050**
Radial	22	74	110	76	103	117
Meshed	22	73 (12%)	115 (27%)	76	103	111

The capacities include existing GW and additional investments in the scenarios, summed up for all countries taking part in the investment optimization. The percentages in the brackets show shares of offshore GW connected to hubs.

TABLE V. WIND GENERATION INSTALLATIONS IN GERMANY

	Offshore wind (GW)			Onshore wind (GW)		
Scenario	**Starting point**	**2030**	**2050**	**Starting point**	**2030**	**2050**
Radial	7	16	19	50	61	68
Meshed	7	22 (40%)	35 (60%)	50	61	68

The capacities include existing GW and additional investments in the scenarios (Germany only). The percentages in the brackets show shares of offshore GW connected to hubs.

V. CONCLUSIONS

This paper has presented a radial and meshed scenario towards 2050 for the North Sea region. A European-wide energy system scenario was used as a background scenario; however, important updates and modification were applied to it. The North Sea region was modelled in detail, with surrounding countries taking part in the energy market. The Balmorel energy system model was used to carry out investment optimization for the scenarios.

VRE generation costs were updated for all generation types, with offshore wind and especially solar PV costs expected to decrease significantly towards 2050. HVDC component costs were modelled and implemented in Balmorel. Detailed modelling of the HVDC costs is especially important in the meshed scenario with a lot of possible lines and hubs; this required MIP modelling in Balmorel.

The capability of Balmorel to model VRE generation and transmission investments simultaneously was used to find optimal shares of different VRE types in the two scenarios, and to optimize the share of radial lines and the utilisation of the meshed structure as part of transmission in the meshed scenario. The results show that going towards a meshed North Sea grid can increase overall offshore wind capacity by around 5 GW by 2050. Germany is seen as the country with most hub connected offshore wind, and with most differences between the radial and meshed scenarios.

Radial transmission lines provide a large share of country-to-country transmission capacity also in the meshed case, which is in line with results shown in [2]. However, a mixture of radial lines and utilisation of transmission infrastructure via the hubs provide the connections from NO and from GB to continental Europe.

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