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North Sea region energy system towards 2050: integrated offshore grid and sector coupling drive offshore wind installations

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Abstract. This paper analyses several energy system scenarios towards 2050 for the North Sea region. With focus on offshore wind power, the impacts of meshed offshore grid and sector coupling are studied. First, a project-based scenario, where each offshore wind power plant is connected individually to onshore, is compared to a meshed grid scenario. Both the amount of offshore wind installed and the level of curtailment are assessed. Then, these results are compared to a scenario with sector coupling included. The results show that while the introduction of a meshed grid can increase the amount of offshore wind installed towards 2050, sector coupling is expected to be a more important driver for increasing offshore wind installations. In addition, sector coupling can significantly decrease the level of offshore wind curtailment.

1 Introduction

The North Sea offers high offshore wind power potential. In addition, several existing and planned transmission lines are located in the region. Consequently, a meshed offshore grid in the North Sea has been proposed as an option for connecting transmission and offshore wind generation investments in the region (Konstantelos, et al., 2017), (Gorenstein Dedecca, Hakvoort, & Herder, 2017), (De Decker, et al., 2011). This paper presents results from comparing such integrated approach to a project-based scenario, where each offshore wind power plant (OWPP) is connected individually to onshore. Another development that can have significant impact on variable renewable energy (VRE) generation is sector coupling (Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018), (Gea-Bermudez, Koivisto, & Münster, 2020), (WindEurope, 2918). With expected increase in electricity consumption, there is more load that can be met by VRE generation. In addition, sector coupling can provide additional flexibility to the power system, e.g., via electrification of heating demand in both individual heating (Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018) and industry sector (Gea-Bermudez, Koivisto, & Münster, 2019).

With focus on the effects on offshore wind power, this paper analyses and compares the impacts of a meshed North Sea offshore grid and sector coupling. Both the expected installation of offshore wind towards 2050 and the level of curtailment due to grid congestion are analysed and compared. The analyses are carried out using a combination of CorRES (Correlations in Renewable Energy Sources) and Balmorel tools. CorRES (Koivisto, et al., 2019) provides the wind and solar generation

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time series used in analysing the impacts of VRE generation on the energy system. Balmorel (Wiese, et al., 2018) takes the CorRES simulations as an input and analyses the expected evolution of the North Sea region energy system towards 2050. With simulated operation of the energy system, considering both the electricity and heating sectors, Balmorel is used to model the behaviour of the system on hourly level. Electricity and heating sectors are optimized jointly towards 2050, with electrification of industry, district heating expansion and electric vehicle penetration also considered. Electrification increases electricity consumption; however, sector coupling has also potential to provide flexibility to the system, which is modelled in Balmorel.

The project-based and the meshed offshore grid scenarios have been published before (Koivisto, Gea-Bermudez, & Sorensen, 2019). However, they are supplemented with recent results on the level of VRE curtailment in the scenarios (Gea-Bermúdez, Das, Pade, Koivisto, & Kanellas, 2019). The presented scenario with sector coupling is new work. In addition to presenting the scenario with sector coupling modelled, this paper contributes by comparing the expected impacts of introducing a meshed offshore grid in the North Sea to the impacts of sector coupling both on the amount of offshore wind power installed and the level of curtailment expected.

The paper is structured as follows. Section 2 describes the methodology used in analysing the North Sea region energy system development towards 2050. Section 3 presents the results for the studied scenarios and compares them. Section 4 provides a conclusion of the presented results.

2 Methodology

All scenarios are analysed using a combination of CorRES and Balmorel, following the approach shown in (Gea-Bermúdez, Pade, Koivisto, & Ravn, 2020), with CorRES providing the VRE time series and Balmorel carrying out the energy system modelling, as shown in Figure 1. The following subsections present both of these tools.

Figure 1. The scenario modelling flow chart.

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2.1 CorRES

CorRES (Koivisto, et al., 2019) is used for simulating the VRE generation time series used in Balmorel. CorRES allows modelling of pan-European scale wind and solar PV generation time series (Nuño, et al., 2018), with both the spatial (between the modelled countries and regions) and temporal dependencies in VRE generation modelled. In addition to analysing current VRE installation, CorRES can be used in analysing the expected impacts of technology development on both the capacity factors (CFs) and the spatiotemporal dependencies in the VRE time series (Koivisto, Maule, Cutululis, & Sørensen, 2019). For the analysed scenarios, wind power is expected to experience both increased hub heights and lower specific power towards 2050. The expected technology developments are linked to the costs of VRE installations, as shown in (Gea-Bermúdez, Pade, Koivisto, & Ravn, 2020), to model the combination of both costs decreasing and technology advancing. For offshore wind, the distance from shore impacts CF and the cost of grid connection, with both AC and DC connections modelled.

2.2 Balmorel

For energy system optimisation, the Balmorel model (www.balmorel.com) is used (Wiese, et al., 2018). Balmorel is an open source (github.com/balmorelcommunity/Balmorel), deterministic and takes a bottom-up approach. The objective function in Balmorel is to minimize total system costs (Gea-Bermúdez, Pade, Koivisto, & Ravn, 2020). Balmorel has been traditionally used to perform joint optimisation of the electricity and district heating sectors, although it is being constantly developed to include additional sectors, e.g. industry (included in this paper), individual heating (not included) and transport (partially included with EVs scenarios based on (Gea-Bermudez, Koivisto, & Münster, 2020). Joint modelling of the electricity and heating sectors allows assessment of benefits from integrating the markets of the different sectors. The setup of the model is similar to (Gea-Bermudez, Koivisto, & Münster, 2020), although with some important differences. The main difference is that the modelling of industry in Balmorel is based in this paper on three temperature levels (low (<100°C), medium, and high (>500°C)) to reflect that not all technologies can satisfy all types of heat demand. Heat pumps are assumed to be capable of satisfying to low temperature demand, CHP low and medium temperature demand, and boilers and electrification low, medium, and high temperature demand. Additionally, the only tax and tariff used in this paper compared to on (Gea-Bermudez, Koivisto, & Münster, 2020) is the CO_2 tax, which pushes VRE penetration on the expense of fossil generation. More details about the assumptions and technologies included in the model can be found in on (Gea-Bermudez, Koivisto, & Münster, 2020).

In this paper, Balmorel is used to perform for the sector coupling scenario: 1) a capacity development optimization; and 2) day-ahead market simulations. In on (Gea-Bermudez, Koivisto, & Münster, 2020), only the first optimization was performed. Investments in generation, storage, power transmission and district heating expansion, as well as decommissioning of generation capacity, are allowed. Due to computational complexity, 8 spread-over-the-year weeks with 1-every-3 hours are used as representative time steps in the optimization. VRE time series are scaled using the approach described in (Gea-Bermúdez, Pade, Koivisto, & Ravn, 2020), so the statistical representation of the full year is kept. Unit commitment integer

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variables are relaxed in this optimization. EV charging is assumed to be non-flexible. The capacity development is then used as input in the day-ahead market simulations.

The day-ahead market simulation for the sector coupling scenario has two steps: 1) full year simulations to obtain storage levels at the beginning of each day, planned maintenance, daily resource allocation; and 2) day-by-day market simulation. Resource allocation is relevant for limited fuels, such as municipal solid waste or biomass. In the full year simulations, all days and 1 every 3 hours are used, EV charging is assumed to be non-flexible, and the relaxation of unit commitment integer variables is applied due to computational limitations. The method is based, and further explained, in (Gea-Bermúdez, Das, Pade, Koivisto, & Kanellas, 2019). In the day-by-day simulation, EV smart charging is allowed. The hourly dispatch values from the day-by-day market simulations are used to compute annual generation, demand, emissions, prices, intercountry transmission flows and wind power curtailment, among others.

3 Results

This section presents and compares the resulting scenarios. The first subsection compares the meshed offshore grid scenario to the project-based one. First, the renewable energy shares and offshore wind installations are compared. Then, the expected levels of VRE curtailment are assessed. In subsection 3.2, the scenario with sector coupling is presented, considering the renewable energy share and amount of offshore wind installations and the expected level of curtailment. The sector coupling scenario does not include a meshed offshore grid.

The project-based and offshore grid scenarios were performed optimizing investments in GB, DK, NO, DE, BE, and NL (the countries in focus are shown in Figure 2), whereas the capacity development for surrounding countries was exogenously given (Koivisto, Gea-Bermudez, & Sorensen, 2019). In the sector coupling scenario, the capacity development was optimized in all included countries. Additionally, compared to the project-based and meshed offshore grid set up, in the sector coupling scenario UK was analysed instead of GB, a different regional set up for DE was defined to capture transmission congestion, and Estonia, Lithuania and Latvia were excluded from the runs to reduce computational complexity. However, the scenarios can still be compared on aggregate level, as is done in the following subsections. The results are shown for the countries in focus (Figure 2), so the results between all analysed scenarios can be compared.

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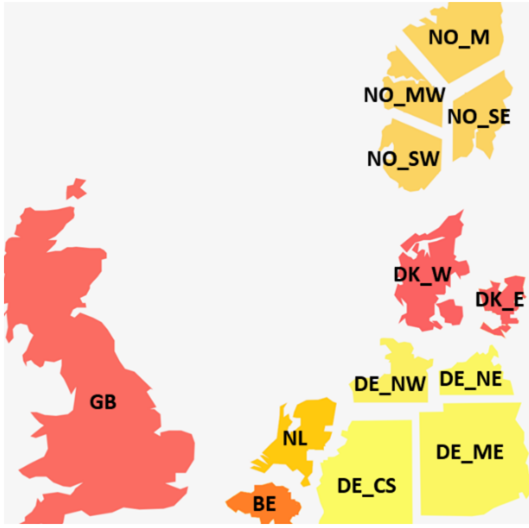

Figure 2. The North Sea region countries in focus (the regional split refers to the project-based and meshed grid scenarios); figure is taken from (Koivisto, Gea-Bermudez, & Sorensen, 2019). The north region of NO (NO_N) is not shown in the graph but included in the aggregated results.

3.1 Impacts of a meshed offshore grid

This section compares the project-based and the meshed offshore grid scenario. The scenarios have been presented before (Koivisto, Gea-Bermudez, & Sorensen, 2019); however, the second subsection adds additional information regarding VRE curtailment. The main difference between the scenarios can be seen in Figure 3: in the project-based scenario, only country-to-country transmission lines are allowed (OWPPs are connected to shore project-by-project); in the meshed offshore grid scenario, meshed connections in the North Sea are allowed in Balmorel investment optimisation (in addition, OWPPs can be connected to the hubs that are part of the meshed offshore grid infrastructure). More information on how the meshed offshore gird is modelled in the Balmorel investment optimisation can be found in (Gea-Bermúdez, Pade, Koivisto, & Ravn, 2020).

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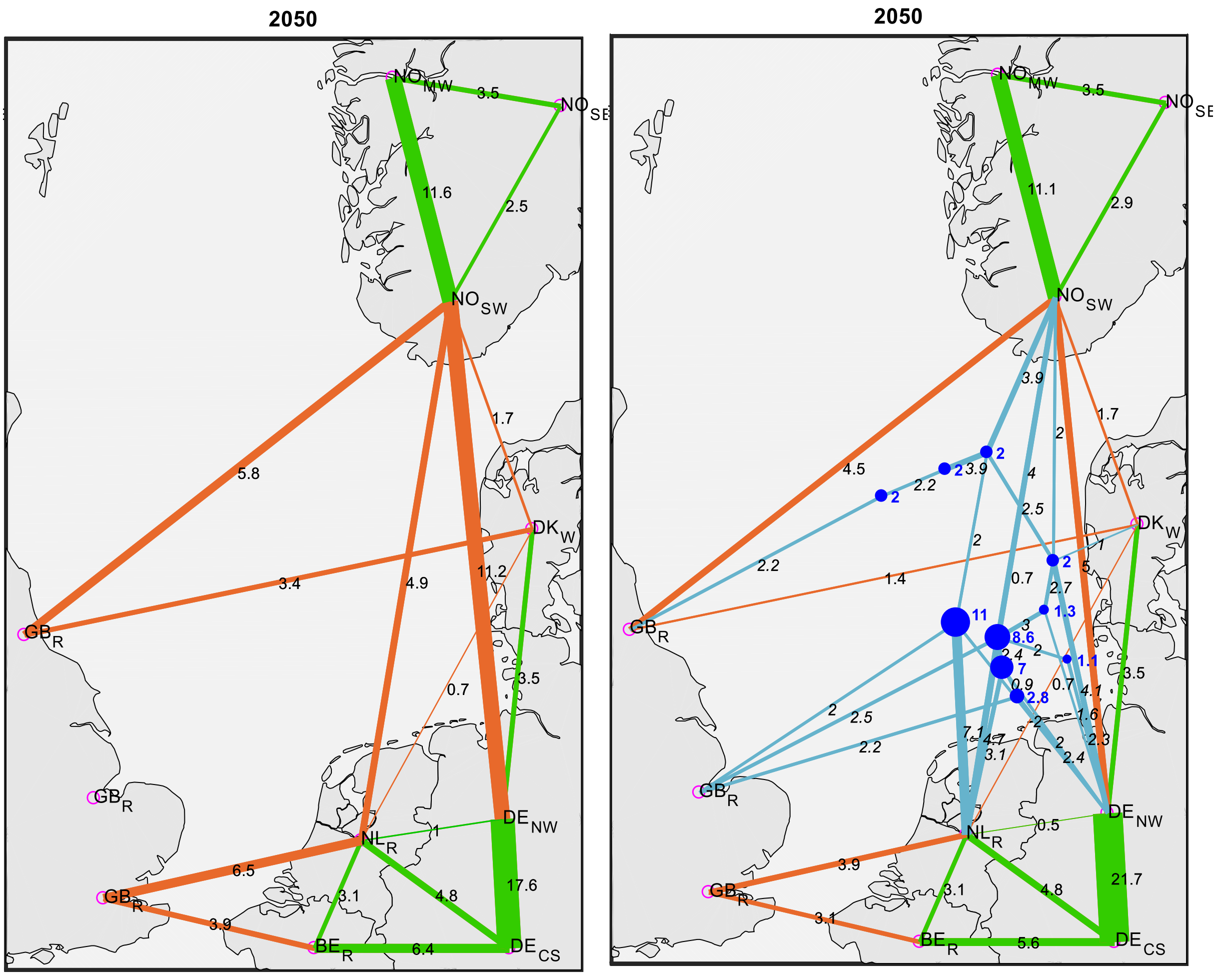

Figure 3. The resulting transmission and hub-connected offshore wind GW by 2050 in the project-based (left) and offshore grid scenario (right). Green shows on-land lines, orange offshore country-to-country lines, light blue meshed offshore lines and dark blue hub-connected offshore wind power installations. The figures are taken from (Koivisto, Gea-Bermudez, & Sorensen, 2019).

3.1.1 Renewable energy shares and offshore wind installations

Aggregate results (for countries shown in Figure 2) for the project-based and meshed offshore grid scenarios are shown in Table 1. It can be seen that in both scenarios the renewable generation share increases close to 90 % towards 2050 (in addition to VRE, renewable share includes hydro and biofuels). Total electricity generation remains on 2020 level, as electricity consumption is not changing significantly in these scenarios. Offshore wind installations increase close to 100 GW towards 2050 in the North Sea region, with meshed offshore grid scenario showing 10 GW more offshore wind installations. The meshed offshore grid scenario is also expected to be cheaper than the project-based scenario (Koivisto, Gea-Bermudez, & Sorensen, 2019).

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Table 1. Aggregate North Sea region results for the project-based and meshed offshore grid scenarios; data from (Koivisto, Gea-Bermudez, & Sorensen, 2019).

Scenario	Year	Total electricity generation [TWh]	Renewable generation share in electricity sector (%)	Offshore wind installations [GW]
Starting point	Approx. 2020	1199	46	22
Project-based	2030	1188	75	64
Meshed		1193	76	69
Project-based	2050	1192	88	92
Meshed		1207	89	102

3.1.2 VRE curtailment

Table 2 shows VRE curtailment results for the project-based and meshed offshore grid scenarios; data is from (Gea-Bermúdez, Das, Pade, Koivisto, & Kanellas, 2019). Especially in 2050, significant curtailment is expected for wind power. The high share of offshore wind curtailment compared to onshore wind may be a result from Balmorel optimisation; offshore wind is expected to have a higher operational (per MWh) cost than onshore, and thus the curtailment of offshore rather than onshore wind is found optimal in the Balmorel run.

For the analysed region, solar PV curtailment is negligible. It needs to be noted that that reported curtailment considers only high-level transmission level grid congestion (between the regions shown in Figure 2), as lower level transmission is not modelled. Thus, there can be additional congestion challenges, especially for generation connected to lower voltage levels, such as solar PV.

Table 2. VRE curtailments for the project-based and meshed offshore grid scenarios. Shares with respect to available production.

Scenario	Year	Onshore wind (%)	Offshore wind (%)	Total wind (%)
Project-based	2030	0.2	2.2	1.2
Meshed		0.2	2.4	1.3
Project-based	2050	0.2	10.3	6.0
Meshed		0.3	10.4	6.5

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3.2 Impacts of sector coupling

This section presents the scenario where the modelling of sector coupling has been included in the Balmorel investment optimization. Figure 4 shows how the heating sector is expected to change towards 2050 as an aggregate for the North Sea region countries in focus. Due to electrification, but also as biofuel use is expanded, coal and gas are almost entirely removed from the heating system. Electrification leads to significant increase in required electric generation, as shown in the next subsection. The possibility to utilise biofuels in the heating sector can be debated; its role is planned to be analysed in future work.

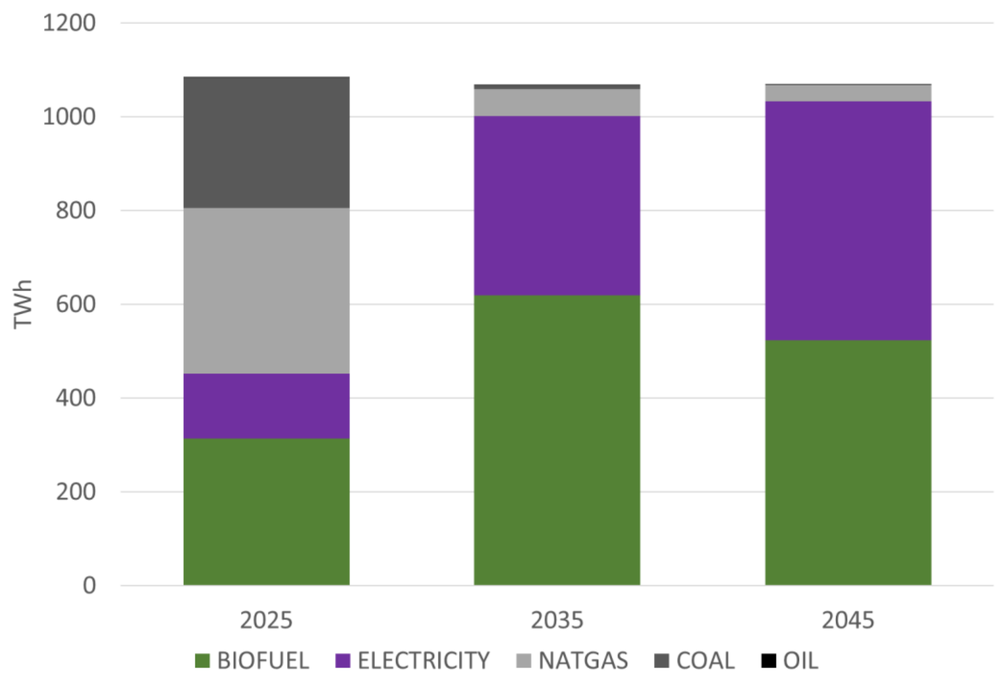

Figure 4. Aggregated heat production per fuel for the countries in focus (countries shown in Figure 2). The industrial sector and individual users connected to district heating are included.

3.2.1 Renewable energy shares and offshore wind installations

As can be seen in Table 3, there is a significant increase of electric generation from the 2020 level shown in Table 1 towards 2045. This can be expected based on Table 4, and it leads to a significant increase in offshore wind installations. Compared to the impact of meshed offshore grid, as shown in Table 1, the effect of sector coupling is expected to be tens of GW of more of offshore wind power. In addition to increasing the overall level of generation (both GW and TWh), sector coupling increases the renewable generation share from around 90 % in the scenarios presented in Table 1 to close to 100 % in Table 4,.

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Table 3. Aggregate North Sea region results for the scenario with sector coupling.

Year	Total electricity generation [TWh]	Renewable generation share in electricity sector (%)	Offshore wind installations [GW]
2025	1284	58	25
2035	1537	94	126
2045	1717	96	158

3.2.2 VRE curtailment

VRE curtailment in the scenario with sector coupling is shown in Table 4. The expected level of curtailment is significantly lower than the numbers reported in Table 2. This indicates increased flexibility of the energy system, as it can absorb more VRE generation (Table 3) while simultaneously reducing the curtailment. The specific reasons for this increased flexibility will be studied in future work; however, the strong coupling between the electricity and heating sector (Figure 4) is expected to be a significant contributor. Curtailment of solar PV is negligible.

Table 4. VRE curtailments for the scenario with sector coupling. Shares with respect to available production.

Scenario	Onshore wind (%)	Offshore wind (%)	Total wind (%)
2025	0.0	0.0	0.0
2035	0.1	0.6	0.4
2045	0.0	1.1	0.6

4 Conclusion

This paper has showed that integrating offshore transmission lines and generation investments in the North Sea region can be beneficial and lead to around 10 GW higher offshore wind installation compared to a project-based scenario towards 2050. Sector coupling is expected to boost offshore wind installations by tens of GW, as electricity consumption increases. In addition, the energy system can benefit from increased flexibility from sector coupling. Indicative results on this were found, as the level of VRE curtailment decreased significantly when sector coupling was considered in the modelling.

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Code and data availability

The Balmorel model is available at: github.com/balmorelcommunity/Balmorel.

Author contributions

Matti Koivisto wrote most of the paper, did the CorRES runs and gave inputs to the Balmorel modelling. Juan Gea-Bermúdez ran the Balmorel optimizations, wrote the Balmorel section of the paper and gave comments. Polyneikis Kanellas helped with the Balmorel runs and gave comments. Kaushik Das gave inputs to the CorRES and Balmorel runs, especially on the day-by-day runs and curtailment analyses, and provided comments on the paper. Poul Sørensen provided comments.

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