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Multi-terminal Offshore Grid for the North Sea Region for 2030 and 2050 Scenarios

PO187

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DTU

Abstract

Offshore interconnectors to neighbouring countries are a crucial element in the Nordic electricity markets. Offshore grids can reduce the overall socio-economic costs of the transition to a sustainable energy system. In a multi-terminal grid, a hub can be connected to multiple countries. Such a hub is a connection point for nearby offshore wind farms. In contrast to connecting each wind farm to onshore, such multi-terminal grid allows the generated wind power at a hub to be transformed to different countries based on the spot market without the need to transfer it first to onshore. The multi-terminal grid also enhances the interconnections between the different countries.

Objectives

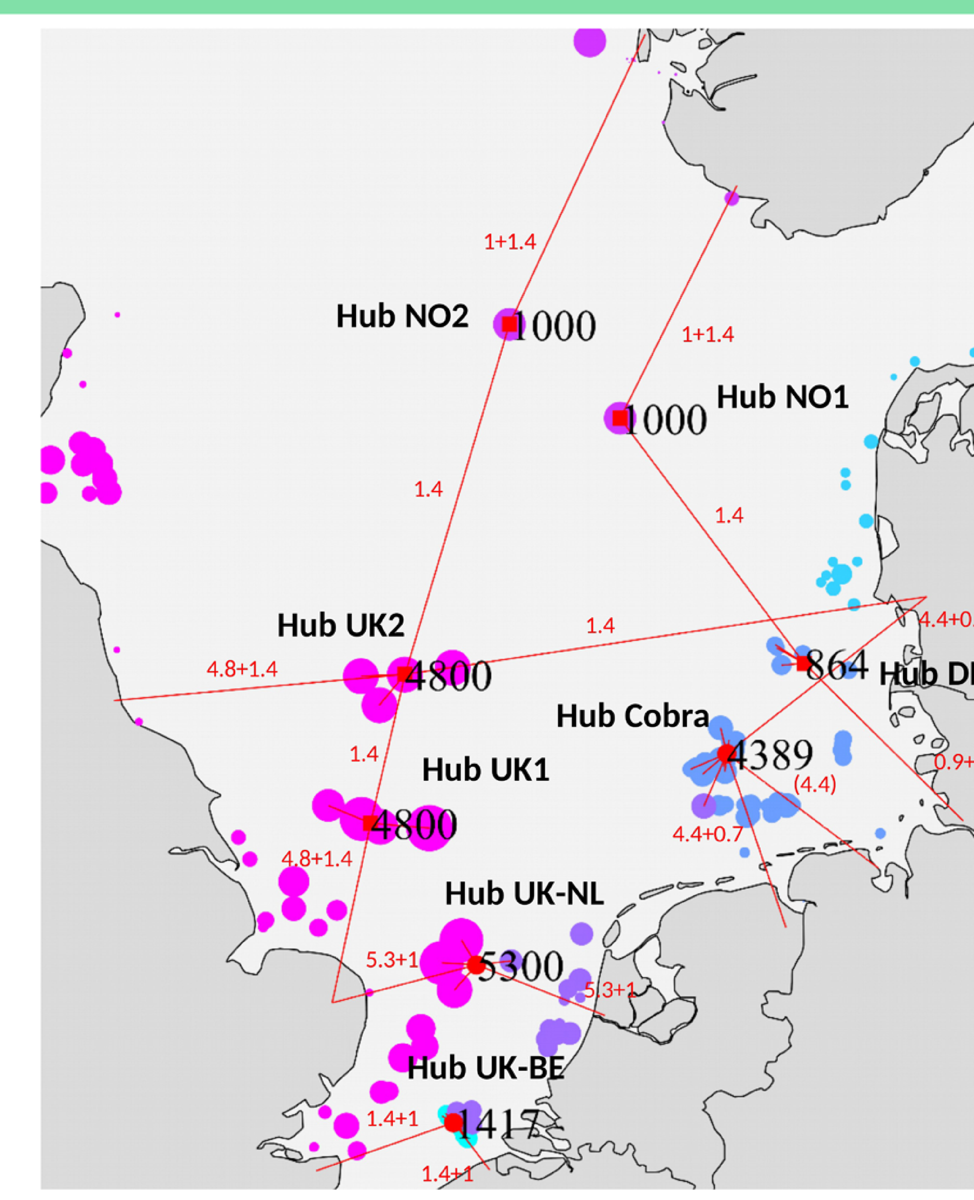
The presented results are the first outcomes of the NSON-DK project [1], which is funded under the ForskEL program administrated by Energinet (ForskEL 2016-1-12438). The project's objective is to study how the future massive offshore wind power and the associated offshore grid development will affect the Danish power system on short, medium and long term in the transition towards a future sustainable energy system.

Methods

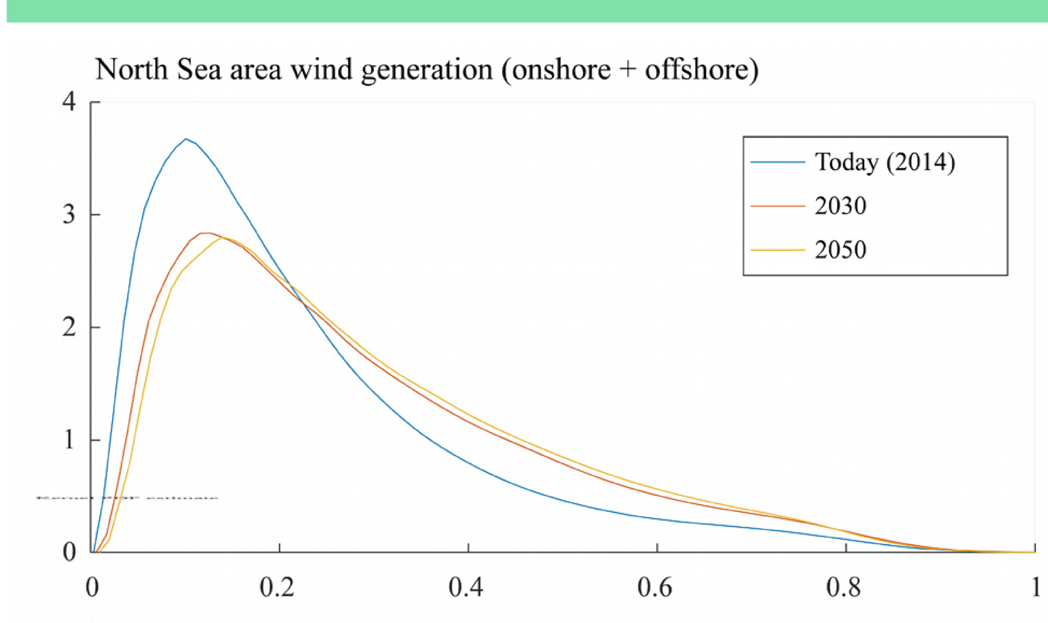
Offshore wind capacities for 2030 are taken from the Wind Europe central scenario [2]. The Nordic Energy Technology Perspectives Flex scenario is used as the basis for the overall energy system for 2030 and 2050 [3]. The 2030 onshore/offshore split is assumed to continue until 2050 (a more detailed modelling is planned). This leads to about 76 GW of offshore wind installed in the countries around the North Sea by 2050.

CorWind is used to simulate wind generation time series for 34 meteorological years. CorWind's capabilities are showcased, e.g., in [4]. In addition to wind, PV generation is simulated. CorWind can be used also to simulate wind power forecasting errors, which will be used later, e.g., in analyzing power system balancing needs (similar PV capabilities are being developed).

A database is used to pin point the mostly likely offshore wind farm locations. Offshore hubs are considered for the major wind farm clusters. A proposed multi-terminal offshore grid can be seen on the right, with installed hub capacities in MWs. It is based on the hubs and planned radial country-to-country transmission lines. The preliminary interconnection capacities, shown in GW, are the sums of the radial transmission lines and wind farm to onshore cable capacities. Later, Balmorel [5] will be used to find the optimal capacities. A radial case, where each wind farm is connected to onshore, is also constructed.



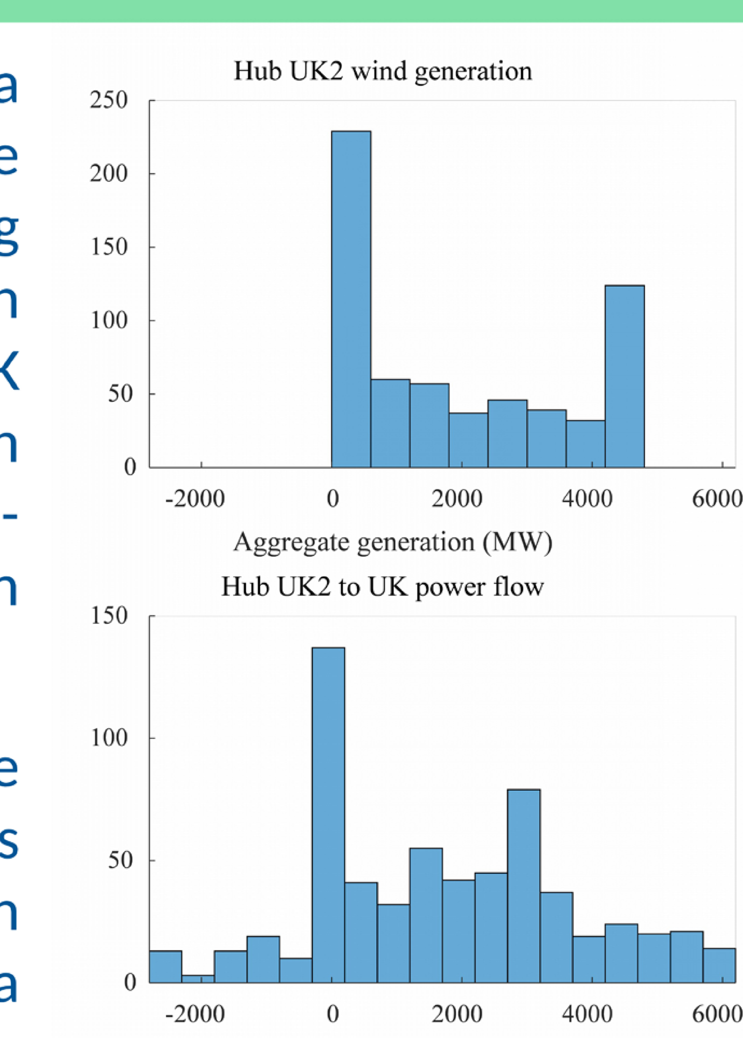
Results



	Hub UK1	Hub UK2	DK	NO	UK
Hub UK1	1	0.86	0.39	0.29	0.76
Hub UK2	0.86	1	0.44	0.36	0.73
DK	0.39	0.44	1	0.41	0.39
NO	0.29	0.36	0.41	1	0.40
UK	0.76	0.73	0.39	0.40	1

Probability density functions (PDFs) of wind generation in North Sea countries are shown on the left. Mean gets higher due to a larger offshore share, and relative standard deviation decreases slightly due to increasing geographical dispersion. Selected spatial correlations in 2050 between offshore hubs and onshore-connected wind generation are reported. UK hubs are correlated quite strongly with other UK wind generation, which indicates that the increased connection to other countries via the multi-terminal grid can be beneficial (as they are less likely to experience high wind generation when the UK hubs are generating the most).

Histogram of wind generation at Hub UK2 is shown on the right. In the radial case the cables to onshore would only be used for transmitting this generation to UK. The preliminary results from Balmorel runs show that in the multi-terminal case the Hub UK2 to UK connection would be used in a more versatile manner with transmission to both directions.



Conclusions

The analyzed scenarios offer a significant amount of offshore wind suitable for hubs. The spatial correlations show that the increased connections to other countries via the multi-terminal grid can be beneficial. The preliminary Balmorel runs imply that the multi-terminal grid design allow better utilization of the interconnection capacities. The scenarios and simulations will be further used in the NSON-DK project for studying electricity markets, power system adequacy, and the balancing and need for reserves in the Danish power system.

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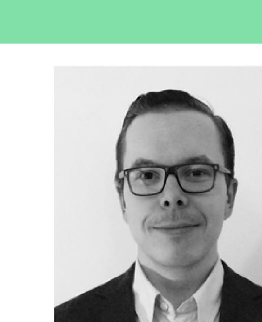

Multi-terminal Offshore Grid for the North Sea Region for 2030 and 2050 Scenarios

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Summary

This paper considers a multi-terminal offshore grid for the North Sea region, where offshore wind farms can be connected to offshore hubs. The presented offshore wind generation scenarios for 2030 and 2050 are based on Wind Europe scenarios. In addition to wind, the assumed underlying energy system scenario for the future is described. Hourly wind and solar photovoltaic generation is simulated for the different scenario years for the analysed North Sea region. The expected variability in wind generation in the future scenario years and how the wind generation in the offshore hubs correlates with other variable renewable energy generation are then presented.

The use of the presented variable renewable energy simulations in the Balmorel energy system tool is described. It is shown that the transmission lines that in the radial case would only be used for transmitting wind generation to onshore, can be used more efficiently in the multi-terminal case. Connecting offshore wind power plants to the offshore hubs in the multi-terminal grid allows the generation to be transferred to many countries, which can raise their market values compared to the radial set-up. The multi-terminal grid can also be used to better connect the different countries around the North Sea region. The use of the presented simulations in power system adequacy and reliability studies is also discussed.

1. Introduction

Offshore interconnectors to neighboring countries are already a crucial element in the Nordic electricity markets. Previous research suggests that offshore grids can significantly reduce the overall socio-economic costs of the transition to a sustainable energy system with significant amounts of offshore wind [1]. This paper considers a multi-terminal offshore grid with wind farms connected to offshore hubs in the North Sea region. The Wind Europe scenario for offshore wind installations is used as the 2030 scenario, and as the basis for a 2050 scenario.

The multi-terminal grid means that a single offshore hub can, for example, be connected to UK, Denmark and Norway. Such a hub is a connection point for nearby offshore wind farms. In contrast to connecting each wind farm to onshore (a two-terminal radial connection), such multi-terminal grid allows the generated wind power at a hub to be transformed to different countries based on the spot market without the need to transfer it first to onshore. Also, when wind generation at a hub is low, the multi-terminal grid can be used as an additional interconnection between the different countries.

Section 2 describes the underlying energy system scenario for the multi-terminal grid set-up, and specifies the scenarios to be studied. The variable renewable energy (VRE) simulations for the scenarios are presented in Section 3. The VRE simulations are then studied using an energy system model in Section 4, with focus on electricity prices and market values of the offshore wind generation. Future work is discussed in Section 5, and Section 6 concludes the paper.

2. Scenario information

This section explains the underlying energy system scenario, on which the offshore multi-terminal grid is considered. It continues to explain the changes made to the scenario, and shows the geographical locations of the OWPPs and how the offshore hub and the multi-terminal grid can be used to connect them to the onshore power system.

2.1. Underlying Energy System Scenario

The energy system scenario used as the basis for the analyses presented in this paper is the Nordic Energy Technology Perspectives 2016 (NETP) Flex scenario [2]. NETP assumptions are in line with those of International Energy Agency for a two degree temperature increase scenario within its Energy technology perspectives 2016 [3]. They correspond with a strong increase of coal and crude oil prices after 2015, and a significant increase of CO2 prices from 2020. Following 2030, fossil fuel prices stagnate, while emission prices increase beyond 80 and towards 136 €/ton by 2050. The development of electricity consumption is projected to be strongly impacted by the assumption of aggressive energy efficiency policies that lead to stagnating consumption despite substantial electric vehicle penetration. However, Denmark is assumed to increase its consumption, by 14% from 2020 to 2050.

In the NETP Flex scenario, the Danish electricity system will have a decommissioning of the remaining coal fired power plants towards the mid of the century. In Belgium and Germany nuclear power plants are expected to be phased-out by 2035. Sweden follows with the phase-out until 2050. Moreover, the economic outlook for nuclear in the other countries is also weak mainly due to strong competition from fluctuating renewable energies. Detailed scenario specification can be found in [2].

2.2. Increased Offshore Wind Installations

It was noticed that the offshore installations in NETP Flex are low, compared, e.g., to the WindEurope (formerly EWEA) 2030 scenario [4]. However, the WindEurope Central and NETP Flex scenarios are relatively similar when considering the overall wind power installations (onshore plus offshore), as can be seen in Figure 1 (the figure includes also countries around the North Sea region, as they affect through interconnections). In regard to offshore wind capacities, a decision was made to use the WindEurope Central scenario for the for 2030. However, the expected annual energy generated from wind in NETP Flex was respected. This lead to lower onshore wind installations in the NSON-DK scenario than in NETP Flex, as can be seen in Figure 1.

Moreover, WindEurope scenario data from [4] is not available for 2050. We assume that the share of offshore versus onshore wind remains the same from 2030 onwards (considering expected annual energy generation). The resulting installed capacities can be seen in Figure 1; the sum of installed onshore and offshore capacity is lower in NSON-DK than in NETP Flex for 2030-2050 because the expected annual generation is kept the same. The resulting installed wind generation capacities for the countries in focus can be seen in Table 1.

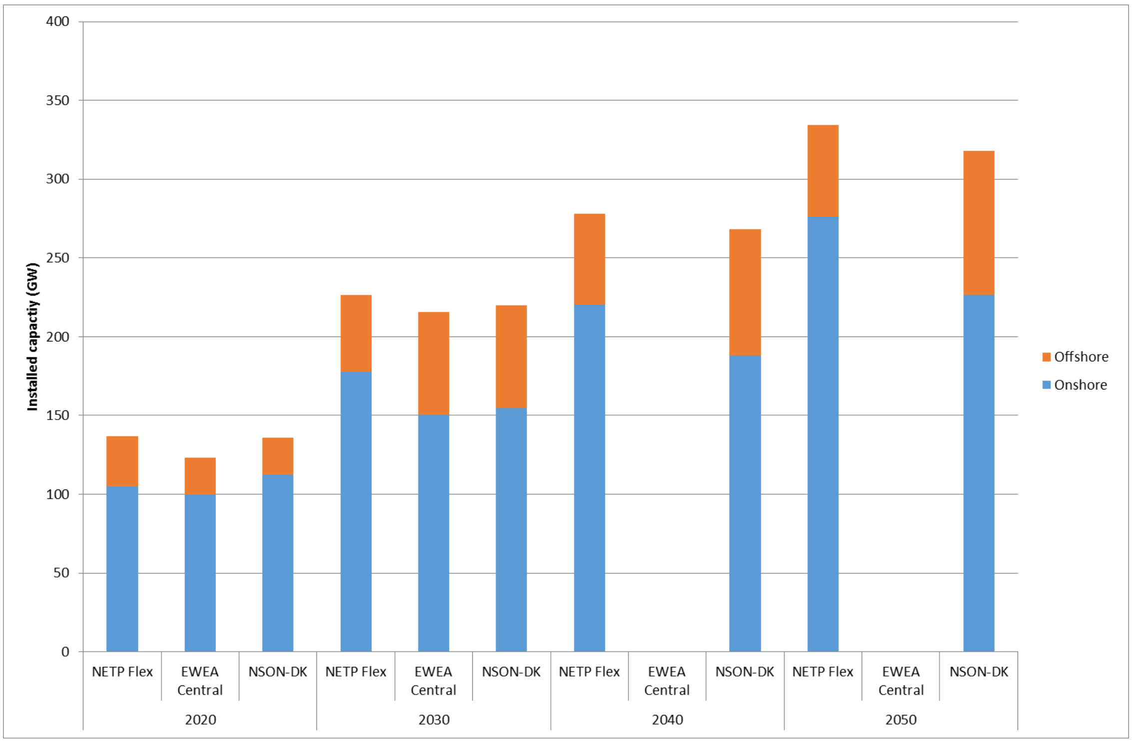

Figure 1: Installed wind generation capacities of the Nordic and Baltic EU-countries, Benelux, France, Germany, the United Kingdom and Ireland; Scenarios: NETP Flex [2], WindEurope Central [4] and the scenario for the NSON-DK project.

Table 1: Installed wind generation capacities in the analysed countries of the North Sea region.

	Offshore wind (MW)						Onshore wind (MW)					
Year	DK	UK	DE	NL	BE	NO	DK	UK	DE	NL	BE	NO
2030	3530	22339	17500	6500	3000	3215	4600	12046	59750	5458	3076	3031
2050	6000	32337	18514	7677	4754	5540	4875	22339	60595	6836	4912	5777

2.3. Offshore Wind Farms at the North Sea Area

The offshore wind farm database at DTU Wind Energy was used to pin point the most likely wind farm locations. The wind farms were selected so that the aggregate installed capacities for the different scenario years are reached for each analysed country in the North Sea Region using the scenario presented in the previous subsection. Offshore hubs are considered for the major offshore wind power plant (OWPP) clusters (or, in the case of Norway for large individual far-offshore OWPPs that are close to planned submarine transmission cables). The planned OWPPs are connected either to these hubs or to onshore based on the distance to the closest hub and to onshore. A multi-terminal offshore grid was then proposed based on these hubs and on planned radial transmission lines between the analysed countries (using Entso-E TYNDP 2014 [5]). The OWPPs and the hubs that are connected to more than one country are shown in Figure 2 for the 2050 scenario. For comparison, a radial case where all OWPPs area connected directly to onshore is also considered.

The transmission capacities in Figure 2 are simple sums: the total OWPP to onshore transmission capacities of the OWPPs connected to each hub (it is assumed here that the OWPP to onshore connections would be 100% of the installed OWPP capacities) plus the underlying interconnector sizes (e.g., 1.4 GW for the NO-UK connection “North Sea Link”). This is a simple way to assess the difference of the multi-terminal (OWPPs as part of the offshore grid) and the radial set-up (interconnectors separated from the OWPP to onshore connections); these values will be updated later during the NSON-DK project, as outlined in Section 5.2.

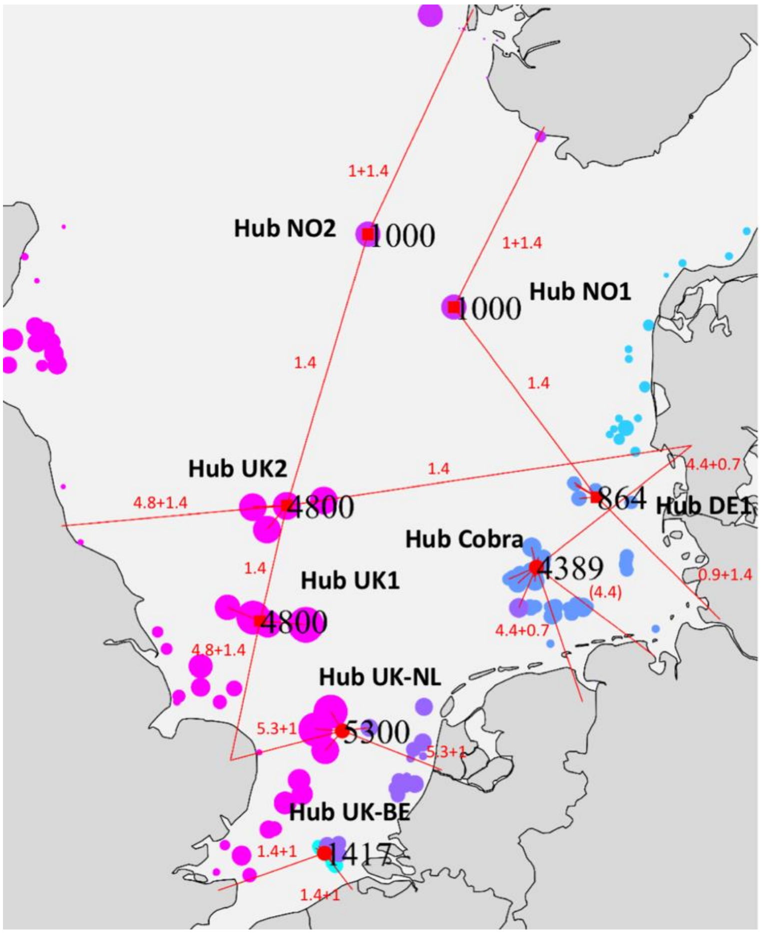

Figure 2: OWPPs in the North Sea area in the 2050 scenario; dot sizes refer to installed capacities and different colours to different countries. For clarity, only the hubs with connections to more than one country are drawn (aggregate installed capacities of these hubs are given in black in MW). The transmission capacities of the lines are given in red (shown as sum of the underlying transmission line capacity and the additional capacity gained from incorporating the OWPP connections to the multi-terminal set-up).

3. Variable Renewable Energy Simulations

This section describes the tools used for simulating the variable energy (VRE) time series for the scenarios specified in the previous section. It then proceeds to give and overview of the simulation results. The VRE generation is simulated for onshore and offshore wind and for solar photovoltaic (PV) generation.

3.1. CorWind

CorWind was used to simulate hourly wind generation time series for the specified scenario years. CorWind, and its underlying meteorological inputs, are showcased, e.g., in [6]. The spatial and temporal dependencies in wind and solar generation are introduced to the simulated generation data by a Weather Research and Forecasting (WRF) model. In comparison to the 30 km WRF model grid used in [6], a 10 km grid was used for the simulations in this paper.

For offshore wind generation, a probabilistic frequency domain model based on [7] was used to generate stochastic wind speed fluctuations with the variability which is not captured by the WRF model. This is important for offshore wind, as the installations are often geographically highly concentrated.

3.2. Spatial Correlations in Wind Generation

An example of spatial correlations between aggregate wind generation in the UK offshore hubs and the analysed North Sea region countries is given in Table 2. The wind generation in the countries consists of both onshore wind generation, and the offshore wind generation connected directly to onshore (i.e., all wind generation connected directly to the countries).

It can be seen that wind generations at the UK offshore hubs are quite highly correlated (0.86). The correlations between the wind generation connected directly to UK and the UK hubs are significantly lower than one (0.73 and 0.76); this gives the possibility of decreasing the overall UK wind generation variability by going far offshore, as lowering correlations can be used for lowering the variability of the aggregate generation [8]. However, from the spatial correlation point of view, even more interesting are the relatively low correlations between the UK hubs and some of the countries that can be accessed through the multi-terminal grid (e.g., 0.29 and 0.36 for Norway). This means that it is rare for wind generation to be very high at the UK hubs and at all of the surrounding countries at the same time. This opens up possibilities for electricity markets in the multi-terminal case, as is discussed further in Section 4.

Table 2: Spatial correlations between wind generation the UK offshore hubs and surrounding countries in the 2050 scenario.

	Hub UK1	**Hub UK2**	**BE**	**DE**	**DK**	**NL**	**NO**	**UK**
Hub UK1	1	0.86	0.60	0.51	0.39	0.70	0.29	0.76
Hub UK2	0.86	1	0.49	0.49	0.44	0.60	0.36	0.73
BE	0.60	0.49	1	0.63	0.37	0.90	0.20	0.60
DE	0.51	0.49	0.63	1	0.74	0.74	0.28	0.48
DK	0.39	0.44	0.37	0.74	1	0.48	0.41	0.39
NL	0.70	0.60	0.90	0.74	0.48	1	0.24	0.64
NO	0.29	0.36	0.20	0.28	0.41	0.24	1	0.40
UK	0.76	0.73	0.60	0.48	0.39	0.64	0.40	1

3.3. Statistics of the Aggregate Wind Generation

Using the scenario specified in the previous section, some basic statistics are given for aggregate offshore wind generation in Table 3 for today and for the future scenarios (the countries are specified in Table 1). The tendency to go further offshore gives a slightly higher capacity factor in the future. At the same time, the standard deviation (std) of the aggregate offshore generation decreases slightly, and the std of the first difference (i.e., 1 hour ramp rate) decreases significantly. Even though the changes are not very significant, the future offers more energy generated from offshore wind with less relative variability. Here, only the changing geographical distribution of the offshore installations is causing the differences in the scenario years. I.e., the numbers given in Table 3 are based on simulations assuming current technology; estimation of capacity factors in the future is discussed in Section 5.1.

Probability density functions (PDFs) for the overall wind generation (onshore + offshore) for today and the future scenarios are given in Figure 3. As the offshore share raises, the mean of the aggregate generation moves higher. The likelihood of very low aggregate generation decreases, but the probability of experiencing higher than 80 % of installed wind capacity generation at the same time increases slightly.

Table 3: Basic statistics of the normalized hourly aggregate offshore wind generation in the analysed North Sea countries (countries shown in Table 1).

Year	Capacity factor	Std	Std of 1st difference
Today (2014)	0.393	0.245	0.0339
2030	0.402	0.244	0.0274
2050	0.406	0.239	0.0259

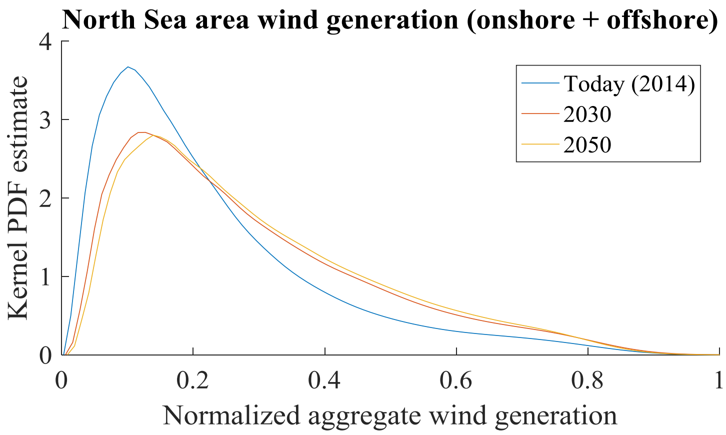

Figure 3: Probability density functions (PDFs) of the aggregate hourly wind generation in the analyzed North Sea countries (shown in Table 1) for today, 2030 and 2050.

3.4. Photovoltaic Generation

In addition to wind, solar PV generation time series were simulated for the analysed region. The correlations reported in Table 4 show that on hourly level, when considering all the hours of the year, wind and solar generation are slightly negatively correlated; this in line with previous studies, e.g., [6], [9]. It can also be observed that spatial correlation in solar generation decreases much slower when distance increases, than in wind generation: spatial correlation between solar generation in UK and Germany is 0.9, while for wind generation it is 0.48. This is due to the similar diurnal pattern in solar generation around Europe (meaning that sunrise and sunset happen roughly at the same time).

Table 4: Spatial correlations between solar PV and wind generation in three example countries.

		Solar PV			Wind		
		UK	DE	NL	UK	DE	NL
Solar PV	UK	1.00	0.90	0.94	-0.18	-0.14	-0.13
	DE	0.90	1.00	0.92	-0.16	-0.18	-0.15
	NL	0.94	0.92	1.00	-0.17	-0.18	-0.16
Wind	UK	-0.18	-0.16	-0.17	1.00	0.48	0.64
	DE	-0.14	-0.18	-0.18	0.48	1.00	0.74
	NL	-0.13	-0.15	-0.16	0.64	0.74	1.00

4. Balmorel Results

The specified radial and multi-terminal cases are compared using Balmorel [10] to find out the effect of the more meshed set-up on electricity prices and market values of the OWPPs connected to the offshore hubs. A more detailed specification of the model set-up can be found in [11], where the VRE simulations presented in this paper have been applied to the Balmorel energy system model.

An example of power flows in the Balmorel model for the multi-terminal can be seen in Figure 4. In the multi-terminal case, the transmission line from the hub UK2 to UK is used in both directions; for transmitting the wind generation from the hub to UK, but also, depending on the market situation, for transmitting the wind generation towards Norway or Denmark. The line can also be used for transmitting power between the three countries, when the wind generation from Hub UK2 is low. In contrast, in the radial case the transmission capacity for transmitting the generation from the same OWPPs can only be used for transmitting the wind generation to UK.

As expected, more meshed case with significant transmission capacities between the analysed countries, allows the wholesale electricity prices to converge toward an average price [11]. Such a convergence can, however, be achieved also by building traditional transmission lines between countries. However, the multi-terminal case seems to give higher market values to the OWPPs connected to the offshore hubs compared to the radial case where each OWPP is connected to a single country [11]. In the multi-terminal case the offshore hubs are connected to multiple countries, so that generation from the OWPPs can be supplied to a wider selection of markets than in the radial case.

Updated scenarios, where the installed generation and transmission line capacities are optimized for both the radial and the multi-terminal case separately, are being developed. Further discussion can be found in Section 5.2.

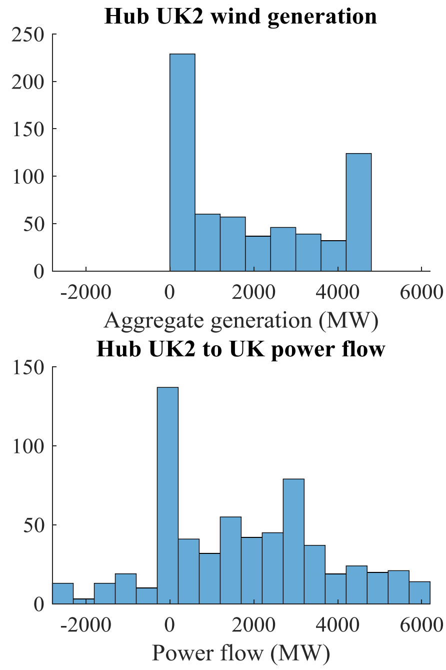

Figure 4: Histograms of wind generation at hub UK2 and the transmission power flow from the hub UK2 to UK onshore in the multi-terminal 2050 case.

5. Future Work

This section describes the future work that will be carried out in the NSON-DK project, based on the preliminary results presented in this paper.

5.1. Estimating Capacity Factors in the Future

The presented simulations are based on current technology. However, modelling of expected technology changes for the future scenario years is underway. Main changes include higher hub heights and lower specific power; both imply higher capacity factors for the future scenario years.

5.2. Optimising the Wind Installations and Transmission Capacities

In addition to using Balmorel for studying electricity prices and market values of OWPPs, it will be used for investment optimization as part of the NSON-DK project. In future work, both the VRE generation capacities and transmission capacities (which in the meshed case also include connections between the hubs) will be optimized. The investments in the multi-terminal and the radial set-up will be optimized separately.

Figure 5 shows the dependency between generation at the hub UK2 and the power flow from UK2 to UK onshore. It can be seen that for the same wind generation, there can be many different values for the power flow (depending on the market situation, as analysed by Balmorel). With the current simple multi-terminal set-up, as shown in Figure 2, the transmission capacities in the multi-terminal grid significantly limit the possible flows. It can be seen in Figure 5 that the bottom right and the top left areas are never reached; currently the main limitation causing this are the relatively low 1.4 GW transmission line assumptions from Hub UK2 towards Norway and Denmark. These values, among other, will be optimized in the future work.

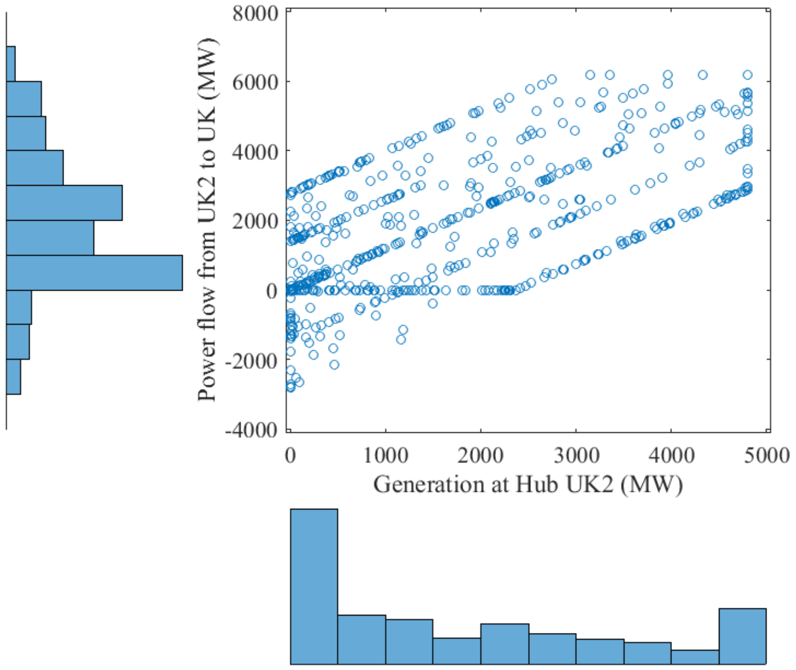

Figure 5: A scatter plot with histograms of wind generation at hub UK2 and the power flow from UK2 to UK onshore in the multi-terminal 2050 case.

5.3. Power System Adequacy, and Balancing and Need for Reserves

Within the NSON-DK project, the presented simulations will be used in studying the system operation aspects related to balancing and need for reserves. In addition to the actual generation time series, CorWind includes the capability to simulate wind generation forecasting errors; similar capability for solar PV is being developed; first results are presented in [12]. The forecasting error simulations will be used in the balancing and need for reserves studies. The analysis of system operation will include the full chain including market balancing of power traders, TSO control using manual reserves and finally the automatically controlled reserves.

In addition, the impact of grid architecture (radial vs. multi-terminal) on system adequacy will be studied. Reliability indexes like “loss of load probability” will be calculated for the different scenarios. As the focus on the NSON-DK project in on Denmark, both the adequacy, and the balancing and need for reserves analyses will be focused on the Danish power system.

6. Conclusion

This paper considered a multi-terminal offshore grid for the North Sea region, where the offshore wind farms are allocated to offshore hubs or connected radially to onshore depending on the distance to the closest hub and to onshore. The presented scenarios are based on WindEurope scenarios. The paper described the expected variability in offshore wind generation in the different scenario years, and showed how the offshore wind generation in the offshore hubs correlate with other VRE generation.

It was shown that the transmission lines that in the radial case would only be used for transmitting wind generation to onshore, can be used more efficiently in the multi-terminal case. With the additional connections to multiple countries, the OWPPs connected to the offshore hubs can raise their market values compared to the radial set-up. The multi-terminal grid can also be used to better connect the different countries around the North Sea region, which converges the wholesale electricity prices of the different market zones toward an average price. The use of the presented VRE simulations in power system adequacy and reliability studies, which will be carried out later in the NSON-DK project, was also discussed.

Acknowledgement

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