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Offshore Energy Hubs in Sector Coupled European Scenarios: Can Large-scale Wakes Hinder the Development?

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***Abstract*—Offshore energy hubs are moving from ideas in academic studies to reality, with Denmark going ahead with a hub or an island in the North Sea and the Baltic Sea. With multi-GW installations planned per hub, they can provide for the expected electricity consumption increase driven by electrification and sector coupling. Large-scale wake losses can be significant, and they get larger as hub size increases. Hub size impacts also the variability of the hub's generation. It is argued that these impacts are significant and should be considered in energy system optimisation. However, the high capacity factors achieved in far-offshore energy hubs still make them attractive in highly sector coupled future scenarios.**

Keywords: Energy system, hub, offshore, sector coupling, variability, wind.

I. INTRODUCTION

Previous works have shown the potential benefits of offshore energy hubs in the North Sea [1], [2]. The topic is moving fast from academic works and reports to reality, with Denmark going ahead with two multi-GW offshore hubs [3]. Electrification and sector coupling increase electricity consumption and flexibility in the energy system [4]-[6]; both aspects are expected to push variable renewable energy (VRE) installations towards 2050. The increased need for electricity generation is expected to increase offshore wind installations, especially if onshore wind expansion is restricted, e.g., due to social acceptance challenges [6]. However, there are also aspects which may hinder the development of offshore energy hubs; this paper analyses the impact of wake losses on large-scale offshore wind generation at the hubs. Although shown to have potentially dramatic impacts on offshore wind capacity factors (CFs) when going to tens of GWs of installations in a limited geographical area [7], large-scale wake losses are often not considered in large-scale energy system optimisation models.

A combination of the Correlations in Renewable Energy Sources (CorRES) and PyWake tools [8] is used to analyse the impact of large-scale wakes on offshore wind generation time series. Hub sizes from 2 GW to 24 GW are analysed, with the impacts on the hub's generation variability also studied. Based on the results, it is argued that the impact of large-scale wakes is significant enough to be included also in large-scale energy system optimisation.

In related work, the hub-size dependent wake losses have been integrated in energy system modelling [9]. The results show that even when the large-scale wake losses are considered, offshore energy hubs are expected to play an important role in sector coupled European energy systems towards 2050. However, when the dependency between hub size and wake losses is considered, a more distributed placement of hubs in the North Sea is found optimal. The best wind resource hub locations far in the North Sea remain attractive for very large hubs even when the increased losses are considered. Although wake losses can be mitigated using lower installation densities, it will lead to larger sea area use, which can be significant when going towards the hundreds of GW of offshore wind installations needed to reach Europe's decarbonization targets [5].

II. MODELING OFFSHORE ENERGY HUB GENERATION

A. *The CorRES model*

The CorRES model is used for simulating the offshore energy hub wind generation time series [10], [11]. It allows hourly generation simulations using tens of years of meteorological data. The meteorological data are interpolated from a 10x10 km grid covering multiple heights to the analysed locations on turbine hub heights [10].

B. *Modelling large-scale wakes*

Different models exist for analysing wakes in offshore wind power plants. The micro-scale wake models available in PyWake are engineering wake models that require the wind power plant (WPP) layout information. Several models are developed to model the wake deficit, added turbulence, blockage effects and wake superposition models [8]. These models are different compared to the meso-scale models based on WPP parametrization available in Weather Research Forecast (WRF) [7], [12], as they rely on modeling the wind plants as momentum sinks and therefore do not model the actual turbine locations. On the other hand, meso-scale models can include the impact of very large plants removing kinetic energy from the atmosphere, which can play a significant role in multi-GW offshore energy hubs. However, such models need to be run on specific wind installation scenarios, where each plant with specific installed capacity is

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included as part of the model specification. They are thus suitable for studying a scenario but are not easily applicable as part of an energy system optimization process to find an optimal scenario. Also, compared to the micro-scale wake models, meso-scale models require more simplified representations of individual plants, as they cannot model wakes from individual turbines. Due to the objective of carrying out energy system optimization, only micro-scale wake models are used in this paper; however, please see Section IV for more discussion.

C. *Large-scale wakes in the CorRES runs*

The analyzed energy hubs are assumed to be circular. Offshore energy hubs of 2 GW, 6 GW, 12 GW and 24 GW are analyzed. A fixed installation density of 7 MW/km^2 is assumed; however, the presented approach can be applied also with different densities. Rated power of 18 MW and specific power of 340 W/m^2 are considered for the turbines at all hubs, at a hub height of 150 m. This aligns the technology approximately to the 2040 assumption in [13].

Wake effects are analyzed following [14], with self-similar Gaussian wind speed deficits, linear wake expansion and quadratic deficit superposition. Each turbine in a hub is considered in the wake modeling, but the resulting wake-impacted power curves are extracted for each 8 x 8 km parts of the hubs. An example of the split of a hub to its parts is shown in Figure 1. The approach provides an individual power curve for each part, so each part can be simulated in CorRES to consider different wind speeds impacting the different parts of the hub at each time step.

Each hub is expected to utilize the most advanced (“Deep”) storm shutdown procedure presented in [15]. In addition to the wakes, electric losses, unavailability and other losses are assumed to be in total 5 %.

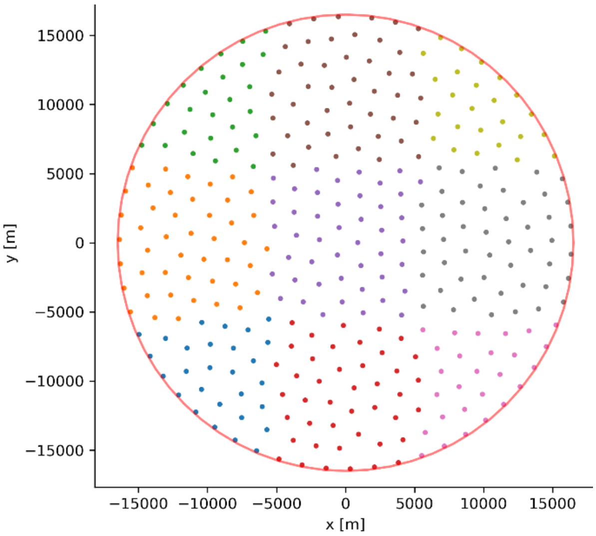

Figure 1. Hub layout of the 6 GW hub. The parts of the hubs are shown in different colors; each part has its own wake-impacted power curve and is simulated separately in CorRES.

III. RESULTS

A. *Capacity factor reduction*

As can be seen in Figure 2, the varying wind resources impact the capacity factors (CFs) of the hubs significantly. The far-offshore hubs tend to have the highest CFs; however, being far from shore, their grid integration costs are the highest, which is considered in the Balmorel energy system optimisation [1] (overview of Balmorel can be found in [16]).

The average reduction in hub CFs, as the hub size increases, is shown in Figure 3. Results for individual hubs follow a similar trend, although the absolute CF levels vary. The “Reference” in the figure relates to a case where an individual turbine with no wake losses is placed in each part of the hub. Such case is not realistic but gives an idea of what the generation could be if there would be no wake losses. On average, the hub CF drops from around 0.55 for 2 GW hubs to 0.53 for 24 GW hubs. Even though the difference is not massive, it is considered important enough to be included in energy system optimisation. Also, the wake losses at very large hubs may be somewhat underestimated with the applied method, as discussed in Section IV.

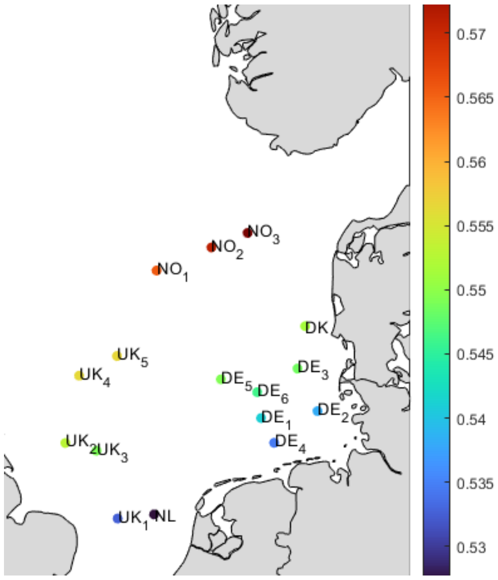

Figure 2. CFs of the analyzed hubs; with 2 GW hub size.

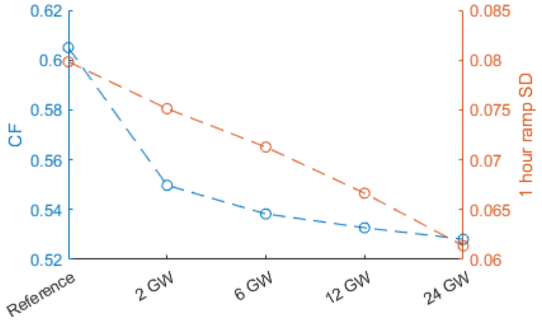

Figure 3. CFs and 1 hour ramp standard deviations (SDs) for different hub sizes (averages of all the simulated hubs). Reference has no wake losses.

B. *Variability as hub size increases*

Figure 3 shows that in addition to CF, variability of the hub's generation also changes as the hub size increases. As the hub covers a larger geographical area, it is natural that the 1 h ramp standard deviation (SD) decreases as geographical smoothening increases. The split of each hub to parts allows such phenomena to be studied from the CorRES simulations. The decrease in relative variability is positive considering system integration of offshore energy hubs; however, the larger hubs still show higher GW ramps, as the decrease in relative variability is limited.

Figure 4 shows a more detailed view of the time series properties of hub generation as hub size increases. Visualised for an example German hub, for a 2 GW and 24 GW hub (with the same central location), the time series seem relatively similar. However, the 24 GW hub shows a somewhat smoother power curve, especially at wind speeds below around 18 m/s. The generation SD is only marginally lower for the 2 GW hub; however, the 1 h ramp SD is significantly lower compared to the 24 GW hub, indicating that especially the higher frequency variability is reduced. Even though controlled storm shutdown procedure is considered, both hub sizes reach complete storm shutdowns during the simulation period.

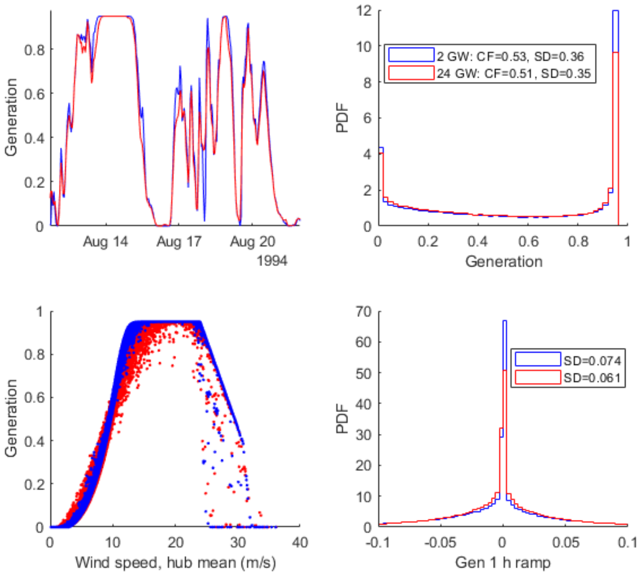

Figure 4. A time series plot (top left), generation histogram (top right), wind speed and generation scatter plot (bottom left) and 1 h generation ramp histogram (bottom right) for an example German hub, when built as 2 GW (blue) or 24 GW (red). The plots are based on hourly simulations from 1982 to 2018.

C. *A single large hub vs. distributed hubs*

To put the level of variability reduction discussed in the previous subsection in perspective, Figure 5 compares two hypothetical scenarios: having 24 GW installed in the highest CF Norwegian hub or having 12 2 GW hubs around the North Sea, reaching the same installed capacity of 24 GW. The overall CF for the two scenarios is similar, with the large-scale wake losses reducing the CF of the large Norwegian hub. However, having the hubs distributed around the North Sea lowers the overall SD; and especially the 1 h ramp SD is significantly lower for the distributed 24 GW compared to having 24 GW in one hub. The higher geographical distribution of hubs lowers the likelihood of having all hubs in a storm shutdown at the same time. In the simulation, the 12 hubs were never simultaneously in a shutdown. Less simultaneous storm shutdowns are linked to having less high frequency ramp events [15].

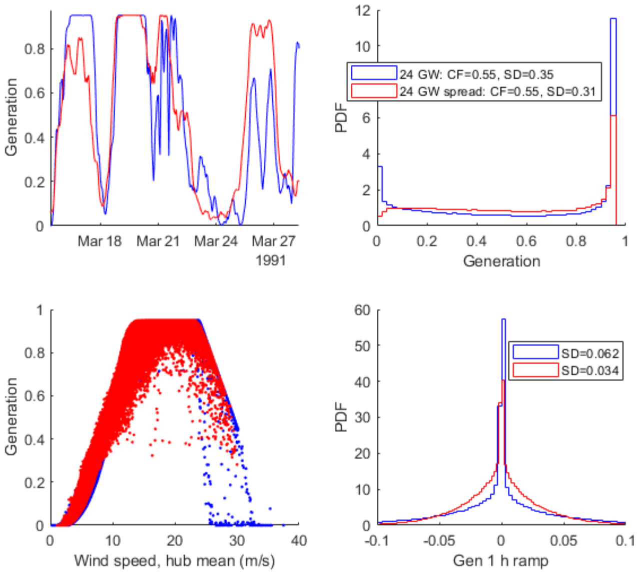

Figure 5. A time series plot (top left), generation histogram (top right), wind speed and generation scatter plot (bottom left) and 1 h generation ramp histogram (bottom right) for a single 24 GW Norwegian hub (blue), and for the aggregate generation of 12 2 GW hubs spread around the North Sea (red). The plots are based on hourly simulations from 1982 to 2018.

D. *Impact on optimal energy system design*

The previous subsections have discussed the hub size and geographical distribution impacts on the hub generation time series. Even though large hubs experience larger wake losses and concentrated hub installations show higher variability, economies of scale can still favour large hubs [1]. This subsection reviews results from [9] to show how these effects influence large-scale energy system optimisation.

Resulting hub installations in a highly sector coupled North Sea region scenario are presented in Table I (more information can be found in [9]) for 2045. When the impact of increasing hub size is included in the optimisation, more hubs see installations, but installed capacity per hub is lower. However, the hubs with the highest CFs (the two Norwegian hubs; see Figure 2) still see the maximum investments allowed in the optimisation (24 GW per hub). Thus, the hubs with the best wind resources seem to be attractive for very large installations even as wake losses increase (however, please see the Discussion section related to uncertainties in estimating wakes in very large installations). The overall hub-connected offshore wind installations are lower when wakes are considered but remain significant. The significant changes in the hub layout in the North Sea shows that hub size impacts should be considered in energy system optimisation.

TABLE I. INSTALLED OFFSHORE WIND GENERATION AT THE HUBS IN A SECTOR COUPLED 2045 SCNARIO

Hub	Hub size impacts included (GW)	Hub size impacts not included (GW)
NO_1	2	3
NO_2	24	24
NO_3	24	24
UK_1		
UK_2	12	24
UK_3	5	12
UK_4	3	2
UK_5	2	
DK	13	24
DE_1	2	12
DE_2	13	24
DE_3	12	24
DE_4	2	2
DE_5		
DE_6	2	
NL		
Total	**116**	**175**

The results are shown in more detail in [9].

IV. DISCUSSION

It is noted that the wake model applied in this paper does not consider all aspects of large-scale wake losses. In ongoing work, the PyWake modelling is updated to the latest models, which also include added turbulence intensity and blockage effects. However, even such models may not fully capture the losses related to very large wind installation, as discussed in Section II B. Modelling the limits on how large a WPP can be before the energy extracted from the atmosphere can no longer be replenished is necessary to ensure realistic energy system optimization. The transition length (or WPP length or diameter) in which meso-scale lack of energy recovery effects become dominant has been determined to be a function of the latitude (Coriolis effects) and of the wind resources, but it is in the order of 30 km [17], [18]. Developing an engineering model to capture the additional wake losses due to meso-scale lack of energy recovery in the atmosphere in PyWake is a possible future research task. This effect is expected to further decrease the CF as hub size increase, as shown in [12].

The CorRES runs applied in this paper are based fully on the meteorological data; they do not include the stochastic simulation part [15]. The stochastic simulation impacts mainly sub-hourly resolution, so it is not expected to alter the presented results significantly. However, the 1 h ramp rates of individual hubs (especially the smaller ones) may be slightly higher than reported.

In this paper, a fixed 7 MW/km^2 installation density is assumed for all hubs. Varying this parameter has a significant impact on the wake losses [7]. Lowering the parameter reduces the wake losses; however, more space would be needed, which can be challenging when going towards the hundreds of GW of offshore wind installations needed to reach Europe's decarbonization targets [5].

V. CONCLUSION

This paper has shown a way of including hub size impacts in the simulation of large-scale offshore wind generation time series. The model is designed to be suitable for energy system optimisation. Larger hubs show larger wake losses, as expected. Increasing hub size lowers generation variability, especially ramps. However, the lowering of variability in one hub, as the hub size increases, is much less than can be achieved when distributing hubs around the North Sea. The results show that large-scale wake losses, and the impact of hub size overall, are important and should be considered in energy system optimisation.

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