Hybrid Versus Radial Offshore Wind Connections: Power Grid Investments in the North Sea

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***Abstract*—To enable offshore wind in the North Sea to take a key, rapid role in the European energy transition, massive grid expansions and investments are required. We consider the impact of such grid expansion in the North Sea on the future European power prices. To this end, we compare, using the power-system model EMPIRE, a scenario in which wind farms can only connect to their own countries, and a scenario in which the wind farms can connect both to other countries and all other wind farms. Uncertainty is implemented in the hourly power load as well as the renewable power production in each system node. The nodes in this work represent the countries in the European power system as well as the major wind farm projects in the North Sea.**

Our results indicate that allowing the offshore wind farms to connect to other countries and wind farms can have a significant impact on the power prices in the different prize zones. These observed effects depend on the level of investments in the North Sea wind farms. Furthermore, allowing for interconnections between countries through the North Sea wind farms significantly increases the investments in the North Sea by means of much larger wind farm capacities and comprehensive grid development. Our results also highlight how certain offshore wind farm nodes may be mainly used for electric power export, rather than covering the domestic power demand. For such wind farms, an interconnected North Sea grid will be critical for attracting large-scale offshore wind investments.

***Index Terms*—North Sea, Offshore wind, Capacity expansion, Energy transition, Optimization**

I. INTRODUCTION

The European energy system is facing an unprecedented transition to adhere with the climate crisis, the need for decarbonization, and net-zero emissions. Lately, the need for changes as been emphasized by the energy crises and the war in Ukraine, shifting the stability of energy supply. Offshore wind is a heralded to be key technology in phasing in large share of renewable generation into the energy mix. The European Commission has proposed to install at least 300 GW of offshore wind power in Europe by 2050 [1] while Wind Europe, a lobby organization for wind power, even proposed 450 GW of offshore wind power [2]. The North Sea is an attractive area for investments due to its favorable wind conditions. It accounts for 212 GW (47 %) in the vision of Wind Europe. Yet, to enable full exploitation of offshore wind in the North sea, substantial grid expansions are required.

Current practice in the development of wind farms is to connect said farms only to the developing country. This implies that potential synergies for utilizing the power lines connecting the wind farms also for power exchange between the different countries are not exploited. The North Sea is however a semi-enclosed sea with countries located in the East, the South, and the West. Consequently, the development of a north sea grid may lead to (i) an increased utilization of the wind resources, (ii) increased utilization of the power lines, and (iii) reduced costs for power exchange between the individual countries.

Various works have considered grid expansions in offshore regions. Huertas-Hernando et al. [3] compare a radial grid (National) with an offshore grid (North Sea Grid). They use two different models to calculate the cost benefits, Net-Op grid optimization tool for determining the infrastructure and PSST for more detailed power flow analyses. The results show than an offshore grid reduces the overall system costs. Torbaghan et al. [4] use their own developed model to compare the transmission system today (National) to an optimal grid solution (North Sea Grid) in the North Sea showing that there are both countries with benefits and losses with an offshore grid. Koivisto et al. [5] use the Balmorel model to analyse the differences between project–based (National) and integrated offshore grid (North Sea Grid). The latter leads to increased investments in offshore wind power. Gea-Bermúdez et al. [6] present a similar analysis as Koivisto et al. [5], but extending the work to explore the savings of a intertemporal compared to a myopic approach, presenting the benefits of a longer planning horizon. They present almost the same results for the intertemporal approach as Koivisto et al. [5], concluding that grid solution leads to cost savings and increased offshore wind capacity in the North Sea.

In this work, we investigate the optimal investments in North Sea wind farms and the associated grid development in the North Sea. Two different cases are investigated and compared. In the first case, the model is only allowed to invest in connections to the developing country. In the second case, investments in transmission infrastructure between the individual wind farms are also allowed. We extend on previous work through a unified investment and operational analysis approach considering also the development of the complete European power system. The specific contributions of our paper are therefore:

i Quantification of cost-optimal investments in main North Sea wind parks.

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ii Quantification of the impact on investments in hybrid vs. radial grid connections, while taking into account existing connections to common European grid.

iii Influence of these investments on power prices in the countries surrounding the North Sea.

II. MODEL

A. EMPIRE

This work uses EMPIRE [7] to analyze the development of the grid. EMPIRE is a capacity expansion model utilizing a stochastic multi-horizon formulation [8] to link operations to investments in a multi-stage setting. EMPIRE creates stochastic scenarios for representative seasons to represent the uncertainty of intermittent renewable generators and electric demand, which in turn drive investments into available generators in Europe. The joint optimization of hourly operations together with long-term strategy ensures effective investment analysis in a specter of energy technologies including intermittent renewable energy. EMPIRE assumes perfect competition while solving the operational decisions.

EMPIRE includes all EU-27 countries excluding Cyprus and Montenegro, but with Bosnia-Herzegovina, Great Britain, North Macedonia, Serbia, Switzerland included. Additionally, Norway is split into five price zones, representing its division in Nord Pool. Data for existing generation and transmission capacity is included in the model. EMPIRE incorporates these data to find the least cost deployment in order to reach the decarbonization targets for the European power sector, as set by the European Commission [9].

Our assumptions in the analysis using EMPIRE are (i) perfect competition, (ii) all costs scale linearly, (iii) one deterministic carbon budget trajectory, in line with EU Commission's goals, and (iv) onshore transmission is capped according to ENTSO-E trajectory.

B. North Sea representation

The North Sea is represented by 14 nodes without any power demand. Investments can be made in bottom-fixed or floating offshore wind only. The 14 nodes are based on all major, currently planned or completed offshore wind projects in the North Sea [10]. All projects are subsequently aggregated into the 14 nodes based on spatial proximity, and are named in Table I. All offshore wind farms are assumed to have the same maximum power density of 6 MW/km^2. The location of the 14 offshore wind farm nodes can be seen in Figure 1a.

The two cases investigated in this work differ in whether the offshore wind farms can only connect radially to its host country shown in Fig. 1a and referred to as the *National case*, or if the wind farms can be hybrid assets that allow them to connect to other wind farms as well as shown in Fig. 1b. The latter is referred to as the *North sea hub* case.

III. RESULTS

A. Investments in North Sea capacity

Figures 2a and 2b show the investments in the North Sea wind farms under the two cases, respectively. We observe that there are no changes for some wind farms, *e.g.*, Borssele, East Anglia and Deutsche Bucht. The maximum capacity constraints for these wind farms are binding even without the additional transmission capacities offered by the North Sea hub case, and so there is no added benefit of additional interconnections.

#	Name	Longitude	Latitude
1	Moray Firth	2.99 °W	58.17 °N
2	Firth of Forth	2.05 °W	56.36 °N
3	Dogger Bank	2.33 °E	54.83 °N
4	Hornsea	1.85 °E	53.82 °N
5	Outer Dowsing	0.91 °E	53.31 °N
6	Norfolk	2.17 °E	52.78 °N
7	East Anglia	1.88 °E	51.89 °N
8	Borssele	3.20 °E	51.96 °N
9	Hollandsee Kust	4.01 °E	52.46 °N
10	Deutsche Bucht	7.18 °E	54.32 °N
11	Nordsøen	7.04 °E	56.28 °N
12	Utsira Nord	4.54 °E	59.28 °N
13	Sørlige Nordsjø I	3.63 °E	57.45 °N
14	Sørlige Nordsjø II	4.94 °E	56.75 °N

TABLE I
NAMES OF OFFSHORE WIND FARMS SHOWN IN FIG. 1A.

The capacities of other wind farms increase considerably in the North Sea hub case. This is especially true for the Norwegian offshore wind parks of Sørlige Nordsjø I & II, and Utsira Nord, where the increased interconnections are necessary for any investments. Some wind farms also experience a more rapid build-up, but their final capacities do not change, *e.g.*, Hornsea. Finally, there are also wind parks whose capacities do not reach their maximum limit in the National case, but do reach their limit in the National Hub case. This includes, *e.g.*, the Danish wind farm site Nordsøen.

Regardless of the case, it is clear that the North Sea wind resources play an important role in the European energy transition. Even in the most limited case, here the National case, the total North Sea wind capacity is approximately 120 GW in 2055. With the added transmission in the North Sea hub case, this capacity grows to almost 180 GW, an increase of about 50 %.

B. Investments in transmission

Transmission undoubtedly plays an important role in the future North Sea grid, and allowing interconnections between the offshore wind farms increases their export flexibility. This allows the energy production to be transmitted to the demand centers, and the wind farms can also serve the role as interconnection points between countries. Comparing Fig. 2b and 3b with Figs. 2a and 3a, we see how this flexibility is valuable.

Particularly for Norway and its wind assets, we see that the North Sea hub case allows for considerably more connection to the grids in Europe and the United Kingdom (UK). This happens primarily via other winds farms, where, *e.g.*, the transmission capacity between Sørlige Nordsjø II and Dogger Bank by the UK and Deutsche Bucht by Germany are among the highest of the hybrid interconnections.

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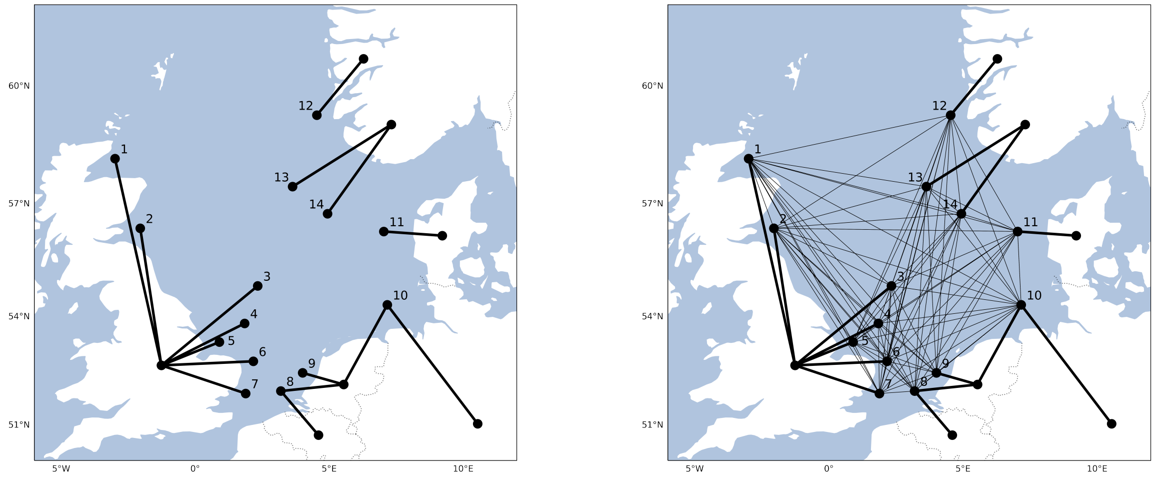
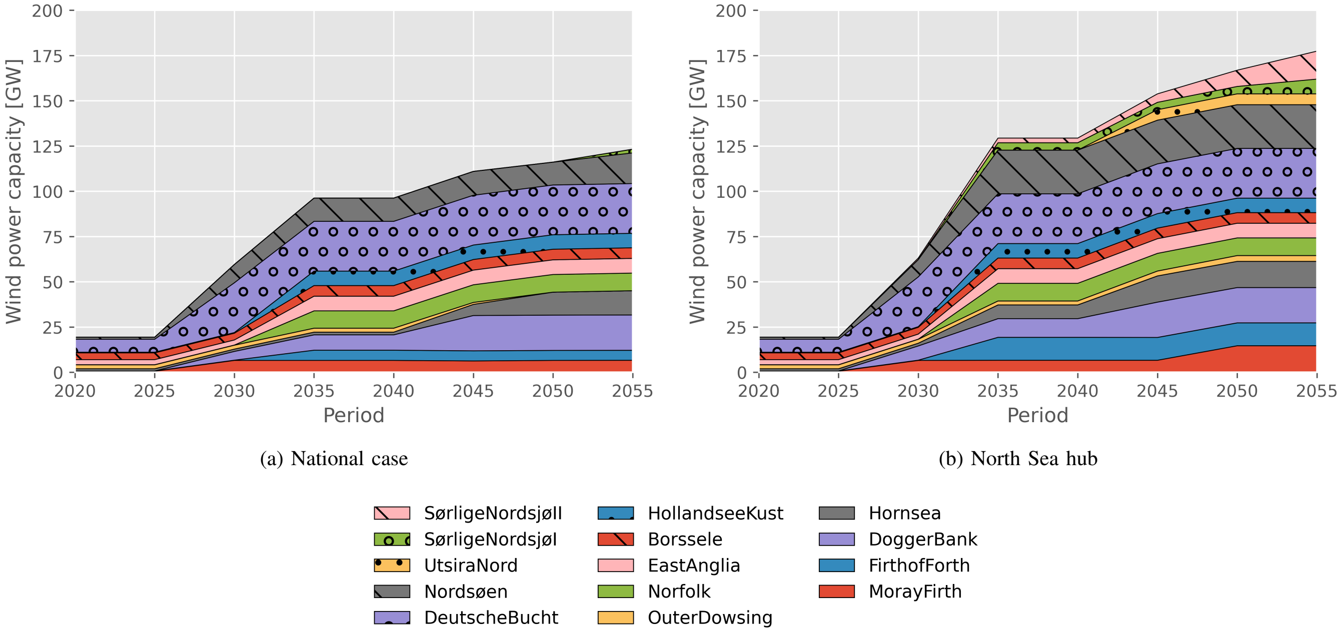


(a) National case (b) North Sea hub

Fig. 1. Comparison of the two cases in this work.



(a) National case (b) North Sea hub

Fig. 2. Investment into North Sea wind parks.

C. *Influence on power prices*

A more connected grid, as represented by the *North sea hub* case, will potentially affect the power prices in the different countries. It is clear from Fig. 3b that the North Sea hub configuration allows for the highest degree of mutual grid integration in this work, as the hybrid wind farm connections allow for greater international power trade. Fig. 4 shows how the yearly average prices in northern Europe differ between the National and North Sea hub cases.

We observe that the prices in Norway and Denmark increase the most, with a power price increase in 2055-2060 of close to 20 €/MWh in southern Norway (NO2). This is a price increase of almost 25 % compared to the National case. On the other hand, the countries closest to the North Sea on the European continent, *i.e.*, the Netherlands, have a price decrease of around 15 €/MWh in the same period.

IV. DISCUSSION

The benefit of allowing for hybrid offshore wind farms as in the North Sea hub case is, from a European perspective, twofold. In the first place, the capacity in the North Sea increases, bringing the EU closer to reaching its goal of 300 GW of offshore wind by 2050. This in turn allows for more renewable generation and thereby lower emissions from

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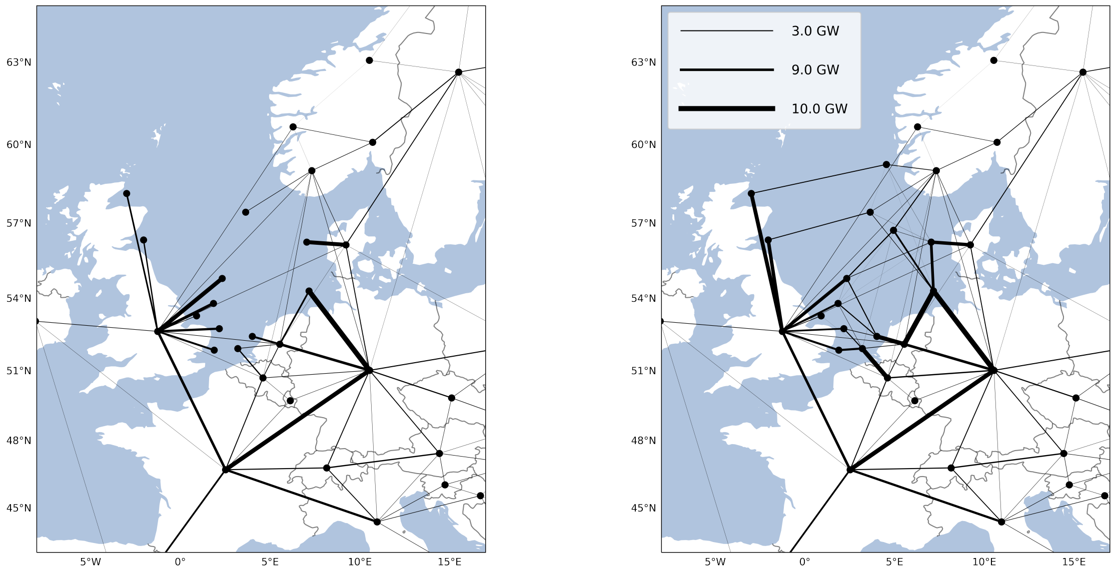

(a) National case

(b) North Sea hub

Fig. 3. Power transmission capacity in 2055-2060 in the North Sea.

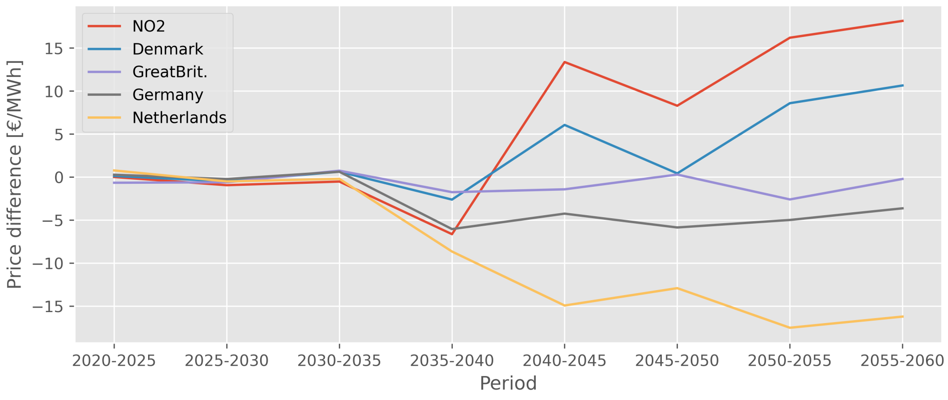

Fig. 4. Difference in yearly average power price between National and North Sea hub cases. Reference is National case.

the European power sector. The second primary benefit is that hybrid offshore wind farms allow for increased power trading among the North Sea countries. In this way, the offshore wind farms may act as power transmission corridors in addition to the direct country-to-country subsea cables.

While the aforementioned hybrid wind farms have prominent economical benefits for Europe, they may be socially and politically controversial in the countries surrounding the North Sea. Fig. 4 shows that the price effects are very different among different countries. Norway, where power prices have typically been very low, experiences the largest cost increase among the North Sea countries. A grid as integrated as the one shown in Fig. 2b will require a high degree of international cooperation. This cooperation may require some form of distribution of benefits in order to make the North Sea grid socially and politically feasible to realize.

EMPIRE is a linear mathematical model in order to make the problem computationally tractable. This means that fixed costs of projects are not included in our model. This is typically not a problem if there are large investments of several units, such as with the offshore wind parks considered in this work. However, this is not true in cases where there are few units installed. This is relevant when discussing the cables seen in Fig. 3b. We observe several cables of low capacity being built directly between wind farms, despite a closely neighboring wind farm having a connection to the same point. In reality, it may be more reasonable that such neighboring wind farms would connect to the third wind farm in series, rather than each having its own dedicated parallel connection.

V. CONCLUSION

In this study, we have shown how the deployment of North Sea offshore wind is affected by whether the wind farms are built as hybrid or radial wind farms. Our results indicate that

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this choice has a tremendous effect on investments where, *e.g.*, some wind farms are only profitable if they can be built as hybrid wind farms.

Allowing hybrid wind farms increases the transmission capacity in the North Sea grid considerably compared to radial wind farms only. However, this leads as well to significant changes in expected yearly average power prices in the North Sea countries, where the prices in, *e.g.*, Norway and Denmark increase considerably, while they decrease in *e.g.* the Netherlands. This uneven distribution of benefits and disadvantages may jeopardize the social acceptance of a North Sea grid in some countries and thereby impede the political decision necessary to facilitate the investments. Considering its growing importance for secure, renewable energy supply to Europe we urge policymakers to consider compensatory schemes and other measures that will allow the realization of a comprehensive North Sea grid.

VI. FUTURE WORK

The North Sea undoubtedly has the potential as an important power source for the European grid. In addition, the wind power may also have additional value that is not captured in this work. For example, wind power from the North Sea may be used to power electrolyzers that in turn produce hydrogen. Hydrogen has vast applications, both as an energy carrier in the power and transport sectors, and as an industrial feedstock. In this way, the North Sea wind power can be used in the decarbonization of additional sectors. The interplay between electrolyzer deployment and North Sea wind capacity may be an interesting extension of this work.

Moreover, the North Sea is only one of the potential offshore wind areas in Europe. Other candidates include, *e.g.*, the Baltic Sea and the Mediterranean Sea. Future work includes to also explore these areas for offshore wind investments together with the North Sea.

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