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Impact of the Offshore Wind Development Plans in the North Sea on the Decarbonization of the European Energy System

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ABSTRACT

Large amounts of offshore wind (OW) power are expected to be installed in the North Sea in the next decades with countries aiming for a total of 300 GW by 2050 as stated in the Ostend declaration. This scale-up will help achieve the decarbonization of the European energy system. However, it is unclear how the introduction of such large volumes of OW will impact the power system, the energy system and the profitability of the OW developments. This paper investigates these issues. A capacity expansion planning model of the European energy system is used to compare cases with limited OW investments, free investments and investments in OW fixed to the targets for 2040. It finds that large amounts of OW mainly reduce the installation of onshore wind, PV and nuclear while causing a total system cost increase across the horizon of about 1%. The offshore grid layout has little impact on the return on investment (ROI), with slightly higher ROIs for meshed offshore grids. Meeting the OW targets increase their ROI by forcing investments to be made at an earlier date, allowing production in periods with higher electricity prices.

Keywords: Offshore Wind, Energy System Planning, Investments Profitability

1. INTRODUCTION

Ambitious plans have been set out for the development of Offshore Wind (OW) in the North Sea with countries bordering it targeting 120 GW installed capacity by 2030 and 300 GW by 2050 according to the Ostend declaration[1] signed by Germany, Denmark, Belgium, the Netherlands, France, Ireland, Luxembourg, the UK and Norway. This massive scale up of power generation will contribute to achieving the decarbonization goals of Europe and significantly impact the whole European energy system. There are, however, large uncertainties regarding the nature of those impacts.

Previous studies have investigated this topic including Martinez-Gordon [1] that has demonstrated benefits for an integrated North Sea grid with and without the interaction with hydrogen through their IESA-NS model. The integration of offshore hydrogen production has been studied by Gea-Bermudez[2], and they find that offshore hydrogen production most likely will play a limited role and that it would be better to transport the energy to shore by HVDC cable. Further studies of the impact of hydrogen production and the topology of the North Sea transmission network are done by Durakovic [3] in which among other aspects the concept of offshore energy hubs have been treated. The paper concludes that the introduction of an energy hub and hydrogen production may significantly reduce curtailment. Reulein [4] also studies the effect of the integration of large amounts of OW using the GENeSYS-MOD model but focuses on the impact on Norway.

This paper aims at addressing the effects of introducing such large amounts of non-regulated renewable energy into the European energy-mix and to evaluate the profitability of those future wind farms. To do this, a case is defined and analyzed using the open energy system model GENeSYS-MOD[2].

This paper addresses the following research questions: 1) What are the impacts of large amount of OW in the North Sea on the European power system, 2) How does the offshore grid layout influences the OW profitability, and 3) How is the profitability of OW impacted by the level of investments in the North Sea?

[1] https://www.regjeringen.no/contentassets/78bfc87bb04044c0933002ad7dd6e0f1/erklaring-energiministere.pdf

[2] https://github.com/GENeSYS-MOD

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This paper is structured as follows: Section 1 gives a short introduction to the topic and a brief literature review, Section 2 details the modelling methodology and data input, Section 3 presents modelling results and discussions, and the conclusions are summarized in Section 4.

2. METHODS

The Julia version of the open-source energy system model GENeSYS-MOD([5], [6]) has been used for this analysis. The model minimizes the cost of meeting a future energy demand through optimizing the investment in and operation of the energy system under emission reduction constraints toward a given planning horizon. It includes modelling of not only the power sector but also the residential heating, industry and transport sectors. The model is initialized based on the current situation for the European energy system. The optimal decarbonization pathways (e.g. investment in power generation, transmission and storages) are calculated.

The model is a large linear program (LP) minimizing the total discounted costs of investing in and operating the energy system. The objective function is formulated as:

$$\min cost = \sum_r \sum_t \sum_y TDC_{r,t,y} + \sum_r \sum_y TDTC\, r, y$$

Where $TDTC$ is the total discounted trading cost and TDC is the total discounted cost, calculated as the sum of the discounted operating costs (DOC), discounted capital investment in generation and transmission (DCI), discounted capital investment in storage ($DCIS$), discounted technology emission penalty ($DTEP$), and discounted salvage values (DSV):

$$TDC_{r,t,y} = DOC_{r,t,y} + DCI_{r,t,y} + DCIS_{r,t,y} + DTEP_{r,t,y} - DSV_{r,t,y}$$

with r, t and y being respectively the sets of regions, technology and years. All costs are discounted to the starting year with a discount rate of 5%.

More details about the model formulation can be found in [5], [6].

The model is run with a 2050 horizon with periods starting in 2018, 2020, 2030 and 2040. Each period is represented by 37 hours, with timeseries sampled (every 241 hours) and scaled from a full year data based on the same method as in the dynELMOD model [7].

An existing dataset for the model is used as a starting point. This dataset stems from the gradual development storyline([8], [9]) of the Horizon 2020 project openENTRANCE.

The dataset is adapted for the context of this study by disaggregating the spatial representation of the most relevant European countries around the North Sea (Norway, Sweden and Denmark) into their respective bidding zones and by modelling offshore generation through 19 additional offshore areas (3 for the UK, 1 for Belgium, 2 for Denmark, 1 for Germany, 2 for the Netherlands, 10 for Norway) where offshore energy generation (and hydrogen production via electrolysis) can be installed. Other countries with a seafront still have the possibility to invest in OW, but not in a specific node, only as part of the existing node. This simplifies the model for areas of lower interest for the study. In addition, we do not include some of the countries further away from the North Sea, as can be seen in Fig. 4.

The OW capacities of countries around the North Sea were updated based on data from the global energy monitor and more specifically, the global wind power tracker[10]. For the residual capacity, we only consider the wind farms installed in or prior to 2018, as 2018 is the initial year of the model. The dataset includes three types of OW: shallow, transitional and deep. Each type has its own capacity limits, CAPEX and timeseries. The initial capacity in offshore nodes is set to shallow as they are mostly located near the coast in low depth waters. The maximum allowed installed capacity in the horizon is set based on the stated goals of the respective countries and distributed spatially based on locations of prospective wind projects and between shallow, transitional and deep based on the type of those prospective projects as mapped in [10]. For the UK, the goal in 2050 is set based on the balanced growth pathway in [11].

We conduct several runs of the model to help answer the research questions. A reference case with no further offshore grid and OW installation after 2018 is first conducted to have a reference to compare the other results with. Then the model is run with a radial offshore grid design and a meshed offshore grid design. In the radial design, the OW farms are connected to the nearest point on land without any interconnection between OW farms in different nodes, while in mesh all connections are allowed. These cases are referred to as *free-radial* and *free-meshed*. Finally, cases where the OW installations are forced to meet the 2040 targets are performed for the radial and meshed grid configurations. These cases are referred to as *fixed-radial* and *fixed-meshed*.

We want to investigate the return on investment (ROI) of OW in each case. We calculate the ROI for the capacity installed in year y_{inst} as follows:

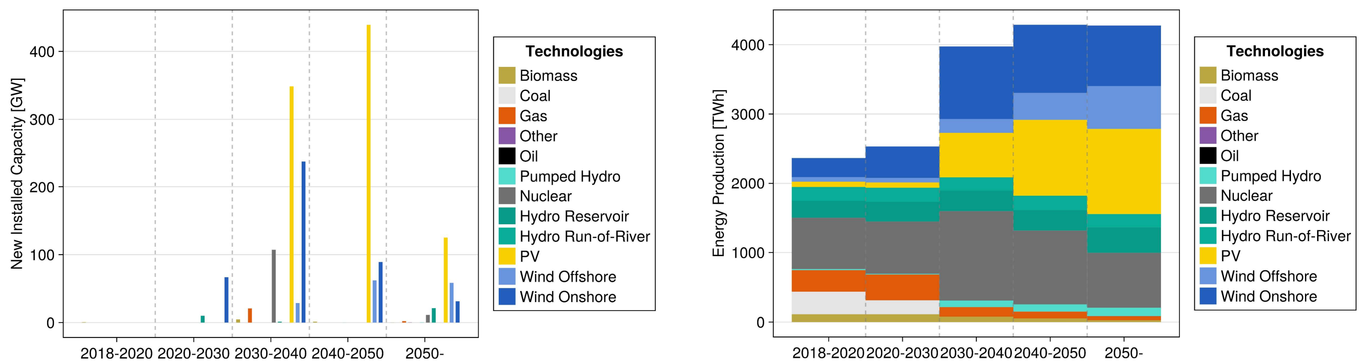

Fig. 1 - New capacity investments (left) and annual power production (right) in each period of the horizon in the reference case.

$$ROI_{y_{inst}} = \frac{\sum_{y_{inst} \leq y \leq L}(Revenue_y - OPEX_y)}{CAPEX_{y_{inst}}}$$

Where: $Revenue_y$ is calculated based on the share of the production in year y from the capacity installed in y_{inst} and discounted to 2018 times the dual value of the demand constraint, which we consider as a proxy for the power price; $OPEX_y$ are the operational cost in year y discounted to 2018; and $CAPEX_{y_{inst}}$ are the investment costs discounted to 2018. For years beyond the horizon, we consider a steady state from 2050. An alternative method considering only the profile made during the study horizon (i.e. ignoring profits from the remaining lifetime of the technology) and considering the salvage value was also considered. However, this approach penalized investments in the last periods.

3. RESULTS AND DISCUSSIONS

This section presents the results from the model runs and a discussion of their implications. The reference run shows the evolution of the power system until 2050 when offshore grid investments in the North Sea do not increase after 2018. Fig. 1 shows the investment in new capacity across the study area in each period until 2050 (on the left) and the yearly power production by technology in those periods (on the right).

With no possibility to invest in OW in the North Sea, major investments in PV of more than 850 GW are made. More than 400 GW of onshore wind and about 100 GW of nuclear power capacity are also installed. Some OW is installed outside of the North Sea representing about 140 GW. Most of the investments take place between 2030 and 2050. These investments result in a power system dominated by renewable production with coal being phased out by 2030 and gas and biomass being significantly reduced. A large power demand increase takes place in 2030-2040, despite the exogenous reduction in specific electricity demand in the model, and due to the electrification of the industry (in particular steel production), residential heating and transportation. Fig. 3 shows the difference between the reference case and respectively the *free-meshed* (top) and *fixed-meshed* (bottom) cases for the capacity additions and power production. In the *free-meshed* case, despite the possibility to invest in OW in the North Sea, very little changes are made to the investments: some OW and solar replaces 7 GW nuclear in the UK. This leads to a slight reduction of nuclear generation replaced by OW and solar. In the *fixed-meshed case*, the amount of OW in the period 2030-2040 is fixed to the ambitions from the Ostend declaration. These 200 GW of OW mainly replace about 300 GW of solar PV and onshore wind. Subsequent periods see a slight increase in solar PV and onshore wind from the base case though, while the OW investments in 2040-2050 completely disappear. Furthermore, the change in power generation also impacts storage and electrolysis, with a large reduction in investments of 450 TWh across all periods and divided between pumped hydro storage (2/3) and batteries (1/3). The geographical distribution of hydrogen production from electrolysis is also affected from 2040 with some production moving from Spain to other countries around the North Sea and with corresponding change to hydrogen storage and 20 TWh additional storage mainly in France and the UK. In terms of power production, the OW replaces a significant amount of PV and onshore wind generation but also a significant share of nuclear. Forcing the investment in OW by 2040 also impacts earlier periods, with a slight increase in production from biomass, gas and coal.

Table 1 – Percentage change between the objective value in the reference case and the other cases [%]

	Free-Meshed	*Free-Radial*	*Fixed-Meshed*	*Fixed-Radial*
Objective Value	-0.0262	0	1.127	1.206

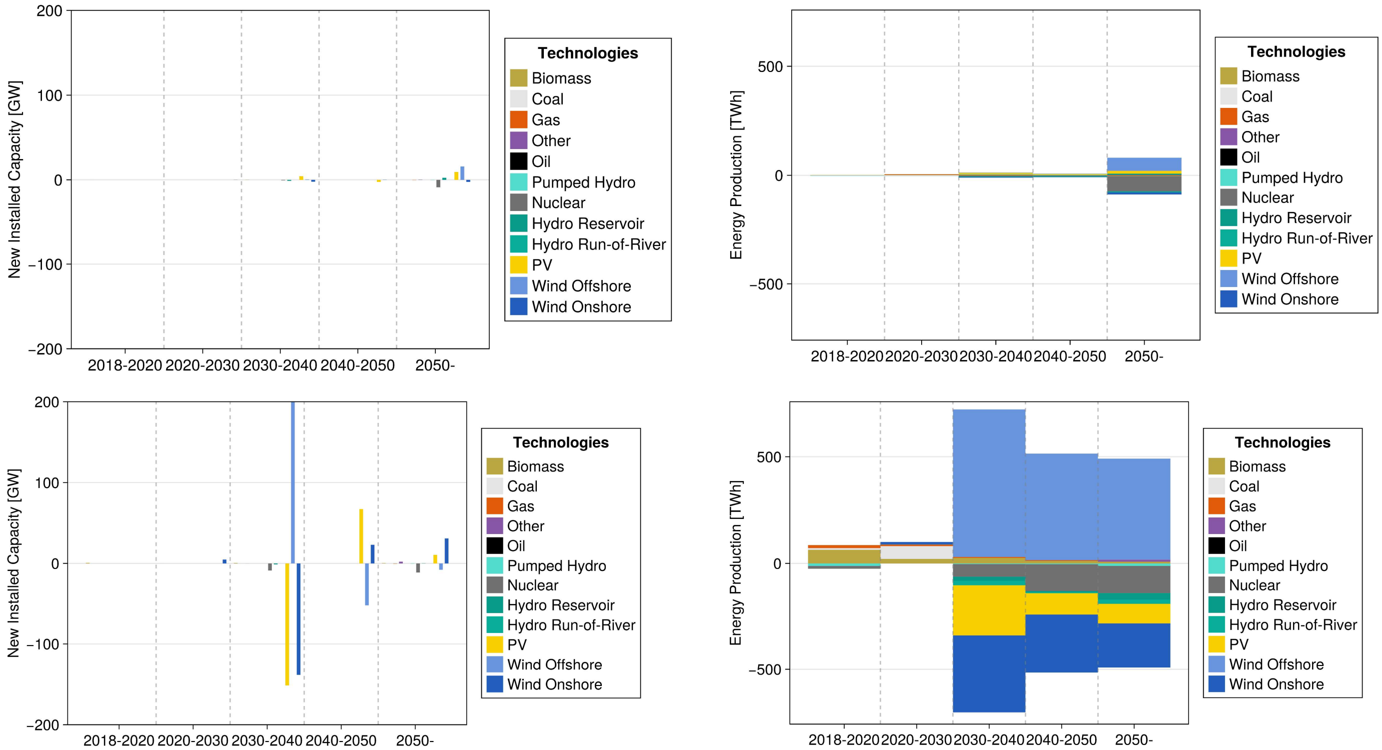

Fig. 3 – Difference of new capacity addition and annual production per period between either the free-meshed (top) or fixed-meshed (bottom) and the reference case

The objective value of the model represents the total system costs. In the reference case, the objective value is 7.629 $\times 10^6$ million euros. The fixed cases lead to a significant increase of the objective value compared to the reference and free cases. The forced investment in OW is therefore not optimal from a system perspective but the additional costs must be weighed against other benefits of OW compared to systems with higher share of onshore wind and PV, such as higher societal acceptance and area utilization.

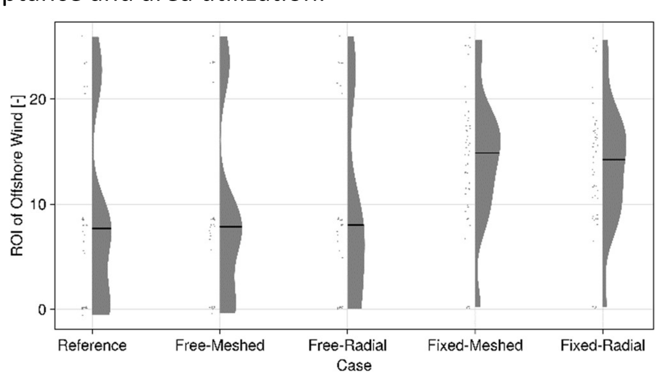

Fig. 2 -Raincloud plot of the return on investment of offshore wind power in the different regions and through the periods.

The ROI of all cases is presented in Fig. 2. A raincloud plot is used for this purpose. It shows the distribution of the ROI for all offshore regions and OW investment year where OW investment happened. For each case, a scatter plot (left) and a violin plot (right) are represented. In addition, the mean is marked via a dark line on the violin plot. The ROI of OW in the reference and in the fixed cases are very similar as can be expected from the results of Fig. 3. For the fixed cases, the ROI median is higher at around 15 instead of 8 (meaning the lifetime profits other the lifetime are 8 times the investment costs). Generally, the ROIs are more spread in the fixed cases while in the free cases, they are more clustered in groups based on the installation years. This is due to the decreasing electricity price towards 2050 allowing more profit and for recouping the additional CAPEX. The ROI in the fixed case is higher than in the reference and free cases due to the higher electricity prices in the period 2030-2040; a period with much more OW investment in the fixed cases than in the other cases. Thus, despite the additional system cost it appears beneficial for OW developers to reach the OW development goals from the Ostend declaration.

Another research question is how the offshore grid design impacts the power system in terms of investment in power production and in offshore transmission capacity. Here we compare the *fixed-radial* and *fixed-meshed* cases. The difference between those cases in terms of capacity addition and production are minimal

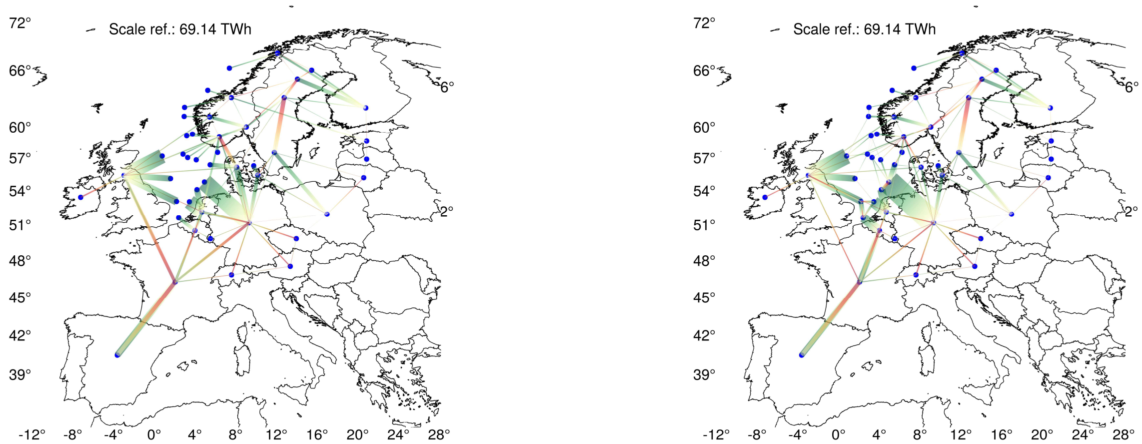

Fig. 4 – Total annual export of power in Europe in 2050 in the fixed-radial (left) and fixed-meshed (right) case. The line width represents the quantity while the gradient denotes the direction of the flow from red/green from the origin node to yellow in the receiving zone. Red and Green are used to distinguish exports to and from the same two nodes. The scale reference is common to both subfigures and indicates the maximum export.

but the transmission of power in the North Sea is affected. Fig. 4 presents the total annual export of power between the nodes in 2050. The radial connections remain mostly unchanged, with some exceptions like Germany which increases its radial connection while also getting connected to Danish and Dutch offshore nodes with respectively 6 GW and 7 GW. The UK, the Netherlands and Belgium also get more interconnected, with 9 GW between the UK and Belgium, 4 GW between the Netherlands and Belgium and 4 GW between the UK and the Netherlands. These capacity increases mainly lead to additional import of offshore wind generation in Belgium. On land, Belgium also imports more power from France in the meshed case. This additional power to Belgium compensates for lower production from nuclear (69 TWh) and PV and onshore wind (18 TWh in total) in the fixed case.

4. CONCLUSIONS

This paper presents the impact on the European power system of a large addition of OW in the North Sea, how the level of investment in OW impacts its ROI, and how the offshore grid layout influences the electricity prices and OW ROI.

The results show that a large amount of OW mainly reduces the installation of onshore wind, PV and nuclear while causing a total system cost increase across the horizon of about 1%. The grid layout has little impact on the ROI, with slightly higher ROIs for meshed offshore grids. Meeting the OW targets increase their ROI by forcing earlier investments, allowing for production in periods with higher electricity prices. Future research should explore the impacts of large share of OW on the rest of the energy system as well as the impact of considering hydrogen production from OW on profitability.

This work focuses mainly on the power system but exploring the impact on the other aspect of the energy system captured by the model (transportation, residential heating and industry) would give insights into other possible consequences of a shift to a power system design including large shares of OW generation. Moreover, the role of hydrogen in such power systems is also not explored, despite being a potential revenue stream for OW farms and affecting their profitability. Socio-economic indicators could be explored to assess the impact of the additional wind farms on job creation and their distribution in the EU for instance.

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