Effects of Offshore Grid Design on Multi-Area Power System Operation

Line Bergfjord, Arjen A. van der Meer, Ana R. Ciupuliga, and Madeleine Gibescu

Abstract — **As a transition towards a more sustainable electricity supply is becoming increasingly urgent, goals are set for an ambitious share of renewable energy sources in countries of the European Union. Offshore wind power development is expected to be an important part of this transition and questions regarding the connection options for potentially large amounts of wind power have fostered the concept of coordinated offshore grid development, e.g. in the North Sea area. Where the wind parks will be built, how the grid should be configured and what effects these choices will have on power system operation, are only some of the many questions arising. This paper aims to provide insight into a possible transnational grid scenario for the North Sea, more specifically into which parameters are important for grid design (e.g. topology and link capacities) and their effects on commitment and dispatch of conventional units.**

Index Terms — **benefit analysis, offshore wind power, transnational grids, unit commitment and economic dispatch.**

I. INTRODUCTION

TODAY'S energy system is experiencing an increasing reliance on renewable energy sources. Environmental concerns and an expected scarcity in fossil fuel resources combined with a worldwide steadily growing energy demand necessitate an energy transition. By issuing directives and setting targets for renewable energy development, the European Union has become an important initiator of this process. The EU has expressed a long term ambition of 80%-95% CO_2 reduction in 2050 compared with 1990 [1]. With its enormous potential within Western Europe [2], wind energy is expected to be an important contributor towards reaching these targets. Offshore wind will receive particular attention in the coming decade, as numerous offshore wind power plants (WPP) are planned to be erected. In addition, increased international power exchanges are expected to improve the efficiency of the pan-European electricity market and at the same time lead to better wind integration, thereby fostering the development of transnational interconnections. The European Wind Energy Association predicts 40 GW offshore wind capacity for 2020 and 150 GW for 2030 [2]. Cost efficient and operationally robust grid connection of these offshore WPPs is considered a challenge, particularly with regard to WPPs located far offshore. Voltage sourced converter based high-voltage dc (VSC-HVdc) technology is available for connecting these distant WPPs while at the same time allowing multi-terminal operation and trade. The topology and transmission capacity of such a transnational offshore grid will depend not only on foreseen WPP locations and installed capacities but also on a perceived trade-off between investment costs and operational cost savings.

Many questions regarding the development, design and effects of such an offshore grid are still unanswered, particularly how a priori choices in topology and WPP location and size, together with transmission grid capacities, influence the operation of conventional and hydro units in the power systems of the North Sea states.

This paper deals with the influence of offshore WPP deployment and transnational grid design on power system operation, with a particular focus on the unit commitment and economic dispatch (UC-ED) of conventional plants. The benefits of a transnational grid compared to a national connection strategy in terms of factors such as higher wind power integration, lower emissions and operation costs and increased link utilizations are determined. For the creation of WPP scenarios, a detailed bottom-up approach is combined with a top-down approach based on national plans. Compared to related research efforts [3]-[5], the combination of scenario development, high-resolution numerical weather simulation data, multi-turbine approach for converting wind speed to power, and the detailed UC-ED benefit analysis constitutes a method that can provide valuable insight into the effects of offshore grid design on power system operation.

A test system was created that resembles three countries of the North Sea region in terms of conventional generation and major interconnected system characteristics on a market level. The North Sea countries included are modelled as separate market areas: Norway (NO), Great Britain (GB) and the Netherlands (NL). Offshore, 3 areas are created to represent the corresponding aggregated wind power of each country (WNO, WNL and WGB respectively). Offshore wind outside the North Sea was not modelled. The zonal grid model is depicted in Fig. 1 for a fully connected offshore grid situation. The model is implemented in a UC-ED tool used to determine the effects of various choices on power system operation. The relative benefits with respect to the radial connection option were evaluated in terms of operational cost savings, emission savings, and additional wind power production that can be integrated without violating any power system constraints. Investment costs are not analysed in this paper.

This research is financially supported by Agentschap NL, an agency of the Dutch Ministry of Economic Affairs, under the research project North Sea Transnational Grid (NSTG). NSTG is a joint project of Delft University of Technology and the Energy Research Centre of the Netherlands.

L. Bergfjord is former exchange student at the Delft University of Technology, recently graduated with a MSc. from the Norwegian University of Science and Technology, Trondheim, Norway (l.bergfjord@ gmail.com)

A. A. van der Meer, A. R. Ciupuliga and M. Gibescu, are with the Delft University of Technology, Department of Electrical Sustainable Energy, Mekelweg 4, 2628 CD, Delft, the Netherlands (e-mail: a.a.vandermeer@ tudelft.nl, a.r.ciupuliga@tudelft.nl,, m.gibescu@tudelft.nl).

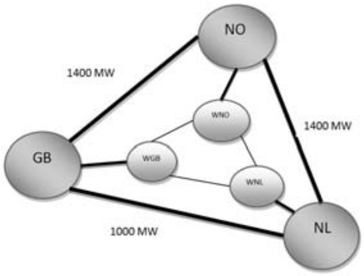

Fig. 1: Multi-area power system topology with an offshore grid.

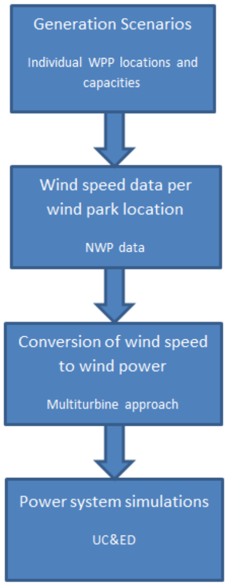

Fig. 2: Flowchart for the power system simulation studies.

This paper is organized as follows. First, each step of the approach is treated in section II, including the data preparation process for the round-the-year market analysis and a thorough explanation of the created multi-area test system, including sensitivities and assumptions. In section III, the simulation results for the various offshore grid topologies are presented. The paper concludes with a summary of the main findings resulting from the benefit analysis performed, and with recommendations for further or similar studies.

II. APPROACH AND STUDY MODEL

The study consists of the following subtasks, also seen in the flowchart in Fig. 2:

1. Create a scenario containing WPP locations and sizes for the year 2025 and 2030
2. Process wind speed time series per WPP location
3. Calculate hourly wind power production based on the given scenarios and wind speed data
4. Include the wind power production into the multi-area power system model and perform a round-the-year UC-ED analysis.

A. Wind Park Scenario Development

Two offshore wind power scenarios for the North Sea for years 2025 and 2030 were created by combining a bottom-up and a top-down approach. With the bottom-up approach information about all existing and planned wind parks in the North Sea was gathered from publicly available sources [6]. The top-down approach was then applied and the total number of wind parks compared and adjusted according to national plans and targets. Finally, the resulting scenarios were compared to similar scenarios created by other European research projects ([3-5] and [7]). The final values are given in Table I. Scenario 2025 is further implemented as base case for the simulation studies in this paper, where only the countries in the gray rows in the table are explicitly modelled.

TABLE I: OFFSHORE WIND DEVELOPMENT SCENARIOS (IN THE NORTH SEA)

COUNTRY	SCENARIO (2025) [MW]	SCENARIO (2030) [MW]
The Netherlands	6214	10308
Great Britain	23095	29965
Germany (NS)	18081	26146
Denmark (NS)	3169	4369
Belgium	1766	3766
Norway (NS)	2680	7180
TOTAL	**55005**	**81734**

B. Wind Speed Data

Wind speed data can be obtained from a range of sources with variations in accuracy and resolution. In this case, high resolution wind speed time series are obtained from a meso-scale regional reanalysis model[1]. With a spatial resolution of 9 by 9 km and a temporal resolution of 10 minutes it is comparable to the data used in the OffshoreGrid study [4]. The wind speed dataset is matched with the wind park locations and the nearest neighbour time series is extracted for each of the defined locations.

C. Power Conversion and the Multi-Turbine Model

Subsequently, the wind speed data is converted to wind power by a multi-turbine approach [8]. This approach is based on regionally aggregated power curves taking into account variations in wind speed and farm smoothing effects, by considering the regional variations in the wind climate and the size of the wind park. Only one measurement point is used per WPP and the single power curve is smoothed into a multi-turbine power curve. The influence of this smoothing is most visible around cut-out speed, between full power and no power, as not all of the wind turbines in a farm reach cut-out speed at exactly the same moment. By applying a Gaussian filter to a single turbine power curve a multi turbine curve is created with the following parameters

$$\sigma_F = \sigma\sqrt{\frac{1}{2}(1-e^{-d_{ave}/D_{decay}})} \tag{1}$$

$$d_{ave} = \frac{2}{3}\sqrt{\frac{A}{\pi}}(1+\frac{2}{\sqrt{N}}) \tag{2}$$

$$y = a\cdot e^{(-\frac{1}{D_{decay}}x)} = 0.4\cdot e^{(-\frac{1}{540}x)} \tag{3}$$

---

[1] Source: Sander+Partner, Switzerland

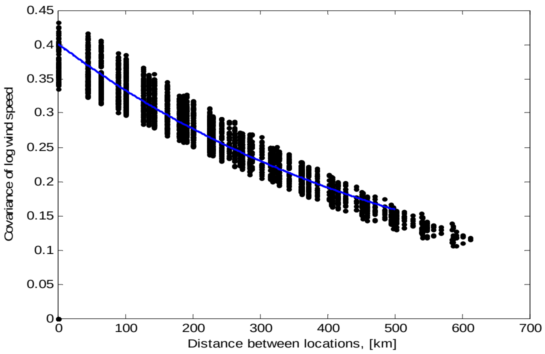

Fig. 3: Correlation of wind speeds versus distance.

This is based on the standard deviation (σ) of the local wind speed, estimated from the wind speed series at the given locations and further modified by taking into account the decay distance (D_{decay}) of the wind speed correlations and the averaged distance (d_{ave}) between the wind turbines. Based on the number of turbines (N) and the area of the wind park (A) the distance between the wind turbines can be calculated according to (2). The decay parameter is describing the decay of the correlation as a function of distance, given by (3) and can be extracted from the covariance versus distance plot by fitting an exponential curve as given in Fig. 3. The filter width can then be calculated according to (1).

A relatively high availability of the wind farm is further assumed and set to 95%. The calculated 10-minute power values are averaged to hourly values, which is the required step size for the power system market simulations.

D. Power System Model

In order to create a relatively realistic test system a range of sources where consulted. ENTSO-e's System Adequacy Forecast (SAF) scenario B [9] provided reference for sizing the generation portfolios and scaling historical load data for the three-area case study presented here. Onshore wind capacities are based on EWEA's scenario for EU 2020 [10] and for Norway based on a study done by the Norwegian Water Resources and Energy Directorate [11]. Offshore wind was implemented according to our developed 2025 scenario and power calculations described in the previous sections. Other data assumptions regarding the power plants are based on [12]. Fuel and emission prices were based on the World Energy outlook [13] published by IEA.

The scenario data is next implemented in PowrSym3^{TM}, a commercially available UC-ED tool used for performing the market simulations. PowerSym is a multi-area, multi-fuel, chronological production cost simulation model for electrical power systems including combined heat and power [14]. The operating cost used includes fuel, emission and start-up costs.

i) Grid Topologies and Simulation Setup

The next step is to choose the basic grid topologies and the simulation scenarios, together with assumptions and sensitivities to be further investigated. As a simplification, the direct country-to-country connection capacities are kept constant at the values depicted in Fig. 1. This is assumed plausible as these connections already are either existing or planned [15].

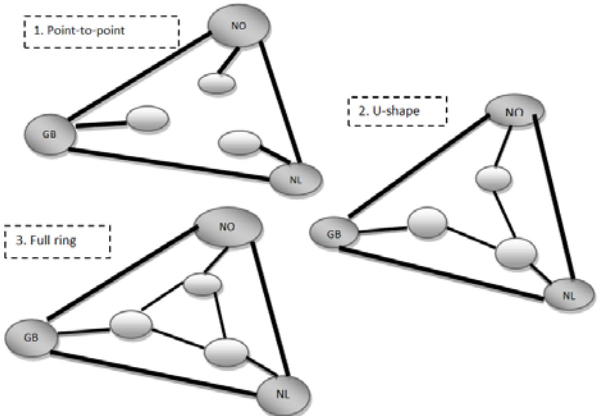

Fig. 4: Offshore grid configurations.

Three development stages are defined, resulting in three prototype grid structures. A grid structure consisting of simple point-to-point connections (between WPPs and landing points) is taken as a base case and further compared to two stages of a meshed grid structure (the U-shape and the full ring shape). These configurations can be seen in Fig. 4. Sensitive input parameters include capacities of WPPs, inter-cluster connections (between WPPs), and connections to shore (between land area and respective WPP area). It should be clear that in general an increase in interconnection capacity leads to more efficient power systems operation, this can be achieved by either increasing the capacities of the direct country-to-country connections or – as is the case in this work – by increasing the capacities of the offshore wind hub interconnectors.

Regarding the capacity of the links interconnecting the wind farm hubs, the point to point configuration is kept constant with a radial link capacity equal to the capacity of the connected wind farm hub, while the capacities in the U-shape configuration and full ring configuration are changed stepwise as shown in Fig. 5. For each of these cases the interconnection capacities between the hubs are rated 25%, 50% and 100% of the smallest connected offshore wind area (S25, S50, S100) and 25%, 50% and 100% of the largest connected wind area (L25, L50, L100). Finally the capacity will be increased enough to represent no capacity constraint (copper plate representation, symbol "C"). All cases are compared to the base case with only direct feeder connections to shore. The resulting changes are calculated as *Delta values* according to (4) and in some of the figures given in percentage according to (5). The base case parameters can be found in Table II.

$$Delta\ values = Case\ values - Base\ case\ values \tag{4}$$

$$Delta\_\% = \frac{Case\ values - Base\ case\ values}{Base\ case\ values} \tag{5}$$

ii) Sensitivity Analysis

Four sensitivity cases are further applied on the chosen grid design, as visualised in Fig. 6. These cases are applied to investigate the effects of changes in wind and hydro power production and possible benefits from coordinated offshore development. The hydro energy production is reduced according to Table III and the wind production is increased according to Table IV.

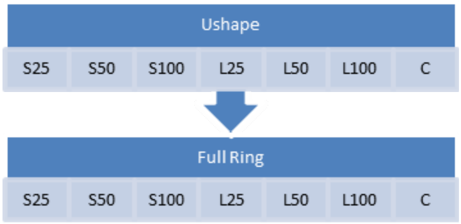

Fig. 5: Simulation steps (S=smallest connected wind hub, L=largest connected wind hub, C=copper plate, numbers give the %).

TABLE II: BASE CASE VALUES

SYSTEM VALUES	BASE CASE
Wind production [GWh]	158547
Wind curtailment [GWh]	26317
Average link utilisation [%]	50%
Production Cost [M€]	14404,5
Emission Cost [M€]	2286,3

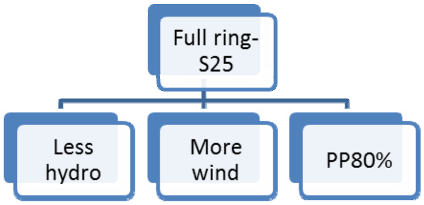

Fig. 6: Sensitivity analysis variants.

TABLE III: CHANGES IN HYDRO ENERGY. VALUES MATCH TYPICAL WET/DRY YEARS IN NORWAY

SENSITIVITY	SIMULATED CASE (NO)	WEEKLY DISPATCHED HYDRO
Wet year (base case)	145 TWh	2800 GWh
Dry year	104 TWh	2000 GWh

TABLE IV: CHANGES IN INSTALLED OFFSHORE WIND POWER CAPACITY

	INST. CAP. 2025 [MW]	INST. CAP. 2030 [MW]	INCREASE [MW]	INCREASE [%]
WNL	6214	10308	4094	66%
WGB	23095	29965	6870	30%
WNO	2680	7180	4500	168%
TOTAL	31989	47453	15464	48%

iii) Assumptions

A well-functioning market is assumed. Power exchanges between the modelled areas are computed according to an energy transportation model subjected to net transfer capacity (NTC) based inter-area link capacities. Transmission capacity is assumed to be adequate within each of the three areas, and connections to areas outside the test system are neglected. Long term optimisation of hydro units is not modelled, and a fixed amount of hydro energy is thus weekly dispatched and optimised.

Despite the simplifications and the limited resemblance with the real Western European power system, the results nonetheless give an insight into which parameters matter for successful design of a transnational offshore network and general results may provide recommendations and a starting point for further and more detailed studies.

III. RESULTS

A. Grid Design

Interconnecting the wind park hubs does in all cases show a reduction in operational cost, as could be expected with increasing connection capacity between market zones. The benefits in terms of cost reduction, emission reduction and increased wind power integration saturates as the capacities of the links are increased. As shown in Fig. 7-9, for the full ring configuration, no additional benefits exist when the inter-hub link capacity exceeds 100% of the capacity of the smallest connected wind park hub (S100).

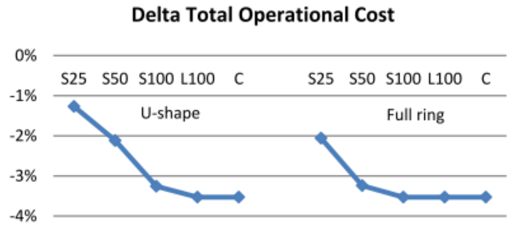

Fig. 7: Change in yearly operational cost relative to PP100 configuration.

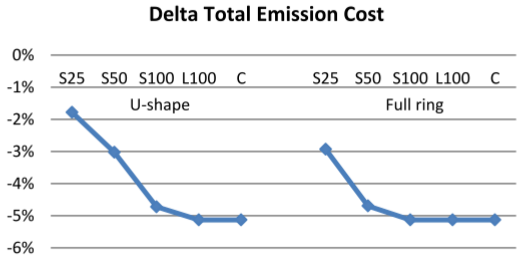

Fig. 8: Change in total yearly emission cost relative to PP100 configuration.

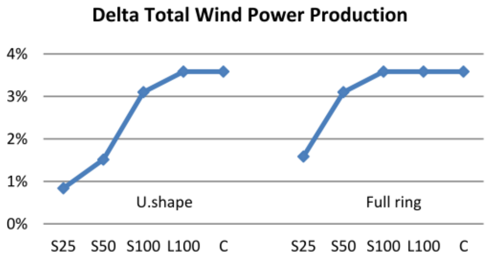

Fig. 9: Change in wind power production relative to PP100 configuration.

Regarding the influence of the connection to shore, the next step is to vary the capacity of these links. The capacities of the interconnectors are kept to S100 and the results for 80,100,120 and 200% link capacity to shore are shown in Fig. 10. These results show little added benefit above 100% (PP100) and this capacity is chosen as the optimal value.

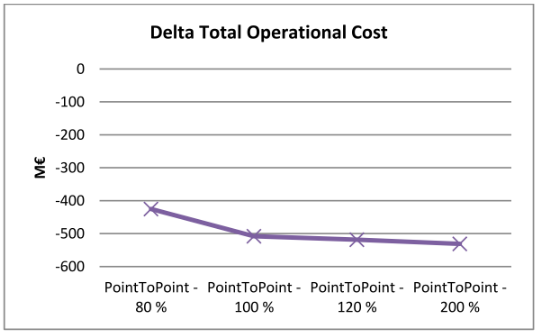

Fig. 10: Delta yearly operational cost, connections to shore.

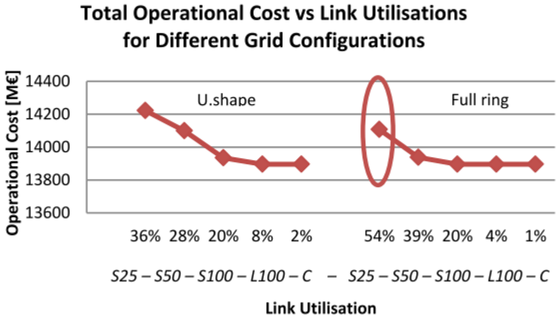

Fig. 11: Total yearly operational cost versus link utilisation for PP100.

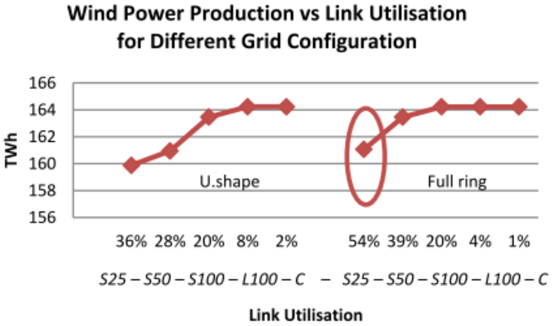

Fig. 12: Wind power production versus link utilisation for PP100.

Although the evaluation in this paper does not explicitly consider investment cost it is important to bear in mind that infrastructural investment cost is a crucial factor in the grid design decision. A trade-off has to be made as increased capacity on one hand results in larger benefits due to a better usage of the available energy resources between the interconnected countries, and on the other hand results in higher investment costs. An alternative way to take this into account is to require a high link utilisation and thereby a certain return on the investment. To visualise the trade-off which needs to be made, the benefits in terms of operational cost savings and increase in wind power production are plotted against the average link utilisation for the offshore grid, as shown in Fig. 11 and Fig. 12, for each case according to the simulation steps given in Fig. 5. To ensure a high utilisation, the ‘full ring S25’ case is chosen for further evaluation in 3 sensitivity analysis variants as described in the following section.

B. *Sensitivity Analysis*

The effects of changes in the meshed grid topology and thereby the changes in interconnection capacity between the wind hubs are firstly assessed. As expected, the results show that increased connection leads to a decrease in system operational cost (Fig. 7) and emissions for all cases. This further corresponds with an increase in wind integration, as pictured in Fig. 9. As mentioned before, the benefits saturate when the capacity of the inter-hub connections are around 100% of the smallest connected wind park hub (S100) for the full ring configuration, and somewhat later for the U-shape configuration -- around 100% of the largest connected wind park hub (L100).

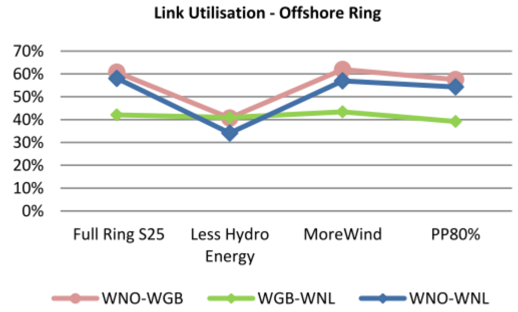

Fig. 13: Offshore link utilisations (3 sensitivity analysis variants with S25).

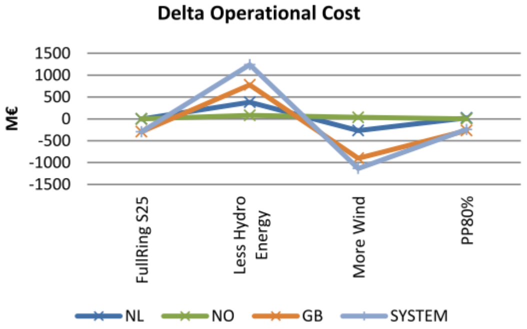

Fig. 14: Delta yearly operational cost relative to PP100, 3 sensitivity analysis variants with S25 full ring.

The link utilisation plot in Fig. 13 shows that in this system, the trade and consequently the offshore grid utilisations are significantly affected by changes in hydro power production (the *LessHydro*-scenario matches the “Dry year” row in Table III). The *MoreWind*-scenario (see “Scenario 2030” column in Table II) represents an expected further development in the wind power deployment which should be taken into account when planning an offshore grid structure. Concerning coordinated offshore grid development, the design of this network seems thus to be capable of handling an increase in the wind power production. It should however be noted that the *MoreWind* scenario resulted in a large increase in curtailed wind.

When comparing the changes in production cost (Fig. 14) for these sensitivity cases, a reduction in available hydro energy leads to higher operational cost, more wind reduces the cost and decreasing the radial connection to shore to 80% seems to have little effect on costs.

In order to explain the changes in production costs it is necessary to look at the changes in generation mix as the cost differs between the generation types. In terms of system reduction in cost and CO_2 emissions the GB area can be seen as the main contributor. This can be attributed to differences in existing generation mix and the consequent changes when adding wind power. The changes in generation mix are shown in Fig. 15. From this it can be seen that coal units in the GB area represent the conventional generation type which is mostly affected by the wind and hydro power and the main share of the production cost changes can be attributed to the changes in coal production.

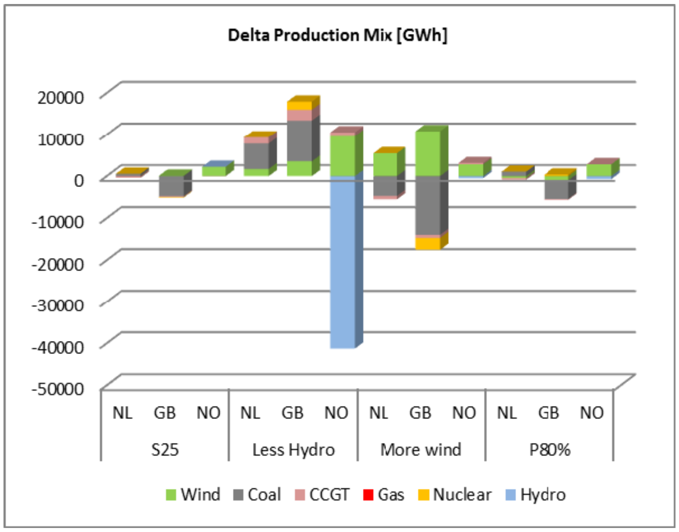

Fig. 15: Change in production mix relative to PP100, 3 sensitivity analysis variants with S25 full ring.

IV. CONCLUSIONS AND RECOMMENDATIONS

This paper presented an approach for assessing the effects of offshore grid design on multi-area power system operation. A simplified three-area study was performed, with generation parks resembling a future scenario for the Netherlands, Great Britain and Norway. The approach followed in this study included a combination of subtasks: a scenario development combining a detailed bottom-up approach with a top-down approach in line with national targets and goals, a high resolution winds speed data set obtained from a numerical meso-scale weather prediction model, a multi-turbine method taking into account variations in the regional wind climate and a benefit analysis based on chronological UC-ED simulations. Each step in this approach contributed to the final outcome.

Various offshore grid topologies were assessed and the most "optimal" combination of topology and respective link capacities was chosen. In general, increasing interconnection capacity leads to reduced operational cost, increased wind power integration and decreased emissions. Starting from a base case without inter-WPP hub links, two other offshore grid structures were analysed: a U-shaped and a ring-shaped grid. In both cases, little value was added when increasing the link capacities to shore above 100 % of the closest wind hub. Reducing the capacities to 80% results only in a slight reduction in benefits, this might however allow for a reduction in investment cost or an increase in wind development. When comparing the full ring and the U-shape configurations, no difference in benefits can be seen at the highest capacities. Benefits of having a full ring may however be more obvious when considering redundancy and reliability criteria. As investment costs were not considered, an alternative method was applied to implicitly take this into account. This was done by a link utilisation versus benefit trade-off. It was shown that an inter-hub capacity equal to 25% of the smallest connected WPP hub ensures around 50% average utilisation of the links in the offshore ring.

The effects on the UC-ED and the grid utilisation are further seen to be sensitive to variations in the generation mix. Reduction in operational cost can mainly be attributed to the reduction of coal power in the British system. Lowering the available hydro energy in Norway leads to reduced utilisation of the offshore ring as well as significantly higher operational cost. Finally, a further growth in offshore wind deployment may considerably increase the operational cost savings.

The example presented in this paper is not complex enough for drawing conclusions on the actual optimal topology of a future North Sea grid but it does provide insight into how to assess it and where the sensitivities lie. For obtaining more reliable results a representation of at least all of the North Sea surrounding countries in the market model is necessary, as well as their interconnection to adjacent countries. Moreover, offshore WPPs in other seas belonging to the modelled countries, and an optimization of the available yearly hydro energy should be considered. In order to say more about the socio-economic benefits of building and operating such a grid, investment costs should be considered and included in a proper cost-benefit analysis performed for the complete life-time of the infrastructure.

V. REFERENCES

[1] EC, "Energy Roadmap 2050 – State of Play", May 2011. Available: http://ec.europa.eu/energy/strategies/2011/doc/roadmap_2050/20110503_energy_roadmap_2050_state_of_play.pdf
[2] EWEA, "Oceans of Opportunity," 2009.
[3] EU, "TradeWind EU-IEE Project," http://www.trade-wind.eu , 2009.
[4] EU, "OffshoreGrid project, http://offshoregrid.eu/ , 2011.
[5] Greenpeace and 3E, "A North Sea Electricity Grid [R]evolution", 2008.
[6] 4COffshore. Global Offshore Wind Farms Database [Online]. Available: http://www.4coffshore.com/offshorewind/
[7] ENTSO-E, "Offshore Grid Development in the North Seas, ENTSO-E views," 2011.
[8] M. Gibescu, A. J. Brand, and W. L. Kling, "Estimation of variability and predictability of large-scale wind energy in The Netherlands," *Wind Energy*, vol. 12, pp. 241-260, 2009.
[9] ENTSO-E, "System Adequacy Forecast 2010 – 2025, Scenario B", www.entsoe.eu, 2010
[10] EWEA, "Pure Power: Wind Energy Scenarios up to 2030," 2009.
[11] NVE, DN, FD, and KYV, "Havvind – Forslag til utredningsområder," 2010 (in Norwegian).
[12] B. C. Ummels, "Power System Operation with Large-Scale Wnd Power in Liberalised Environments," Ph.D. Dissertation, Delft University of Technology, 2009.
[13] International Energy Agency. World Energy Outlook. Available: http://www.iea.org
[14] Operation Simulation Associates; Inc., "PowrSym3 User's Manual v361h6," Technical Report.
[15] ENTSO-e, "Ten Years Network Development Plan," Available: https://www.entsoe.eu/fileadmin/user_upload/_library/position_papers/110202_NSOG_ENTSO-E_Views.pdf, 2010.