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North Seas Offshore Network (NSON): Challenges and its way forward

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Abstract. Serving a twofold purpose, integrated offshore grids can facilitate the connection of offshore wind generation with onshore networks as well as the interconnection of asynchronous market areas for power trade. With a growing amount of offshore wind generation being deployed in Northern Europe, the relevance of a North Seas Offshore Network (NSON) increases, particularly in light of high cross-sectoral decarbonisation targets. To investigate future deployments of offshore grids in the North Seas, the national NSON project in Germany developed a closely linked modelling chain involving several stages: market- and technology-based grid planning, offshore grid validation, and onshore grid repercussions. Following an introduction to the NSON Initiative, a comprehensive overview of the modelling stages is given. Important subjects for further research which could be identified while working on the NSON-DE project are discussed afterwards. Main issues include flexibility and uncertainty in future energy systems, market integration, cost-benefit sharing, as well as robust grid planning and enhanced grid operation methods, especially for combined AC/DC-networks.

1. Introduction

In order to make low-carbon technologies affordable and competitive, the North Seas Offshore Network (NSON) Initiative follows the European Strategic Energy Technology Plan (SET-Plan) [1] and addresses the need for European cooperative research and demonstrations projects taking up new energy technologies. By facilitating a sustainable and well-coordinated grid expansion on the European level, an offshore grid in the North Seas regions could contribute to the decarbonisation of the European energy sectors. In order to enhance security, stabilise prices, and increase cost efficiency, offshore grids serve the twofold purpose of integrating offshore wind power and connecting national energy markets. Several studies have already shown that a common undertaking, with shared costs among the different stakeholders over a long time frame, will be considerably cheaper than a case-by-case approach, see [2]. The overall cost will be minimised and future industrial initiatives in the region could see a reduced integration cost.

An integrated and potentially meshed offshore grid topology involving High Voltage Direct Current (HVDC) transmission and Voltage Source Converters (VSC) enabling meshed DC-structures are regarded as the most suitable technology for super grids in Europe [3]. Since the beginning of the NSON Initiative, scientific progress has been made, novel developments have

been reported, and additional insights have been gained on both the market and technology layers of a potential NSON.

The key objective of this article is to present the overall approach taken in the German NSON research project, focusing in particular on the closely linked modelling stages. At the same time, existing and new challenges associated with the deployment of an offshore grid in the North Seas will be reviewed. The analysis will identify and highlight remaining knowledge gaps in current research projects investigating a potential NSON.

The remainder of this article is structured as follows: Section 2 introduces the NSON Initiative by outlining its vision and partners. To give a comprehensive overview of the German NSON project, its approach and its focus of work are presented in Section 3. On this basis, Section 4 outlines new and remaining research challenges concerning the deployment of a future offshore grid in the North Seas region. Section 5 concludes the article.

2. Description of the NSON Initiative

Given the common national interests of pursuing an offshore grid in the North Seas region, the NSON Initiative can be understood as a research, development, and deployment program. It follows a new model for cooperative research activities in Europe, called the "Berlin Model" [4], pursuing nationally funded projects which are guided by a simple and target-oriented implementation.

2.1. Vision and objectives

The NSON Initiative aims to foster the realisation of an efficient and secure energy transmission system in the North Seas region, called the North Seas Offshore Network (NSON). This features an analysis framework for a step-wise transmission system deployment approach using hybrid technologies and a cost-benefit sharing market design that is attractive to all participants and investors.

The main objective of the NSON Initiative is to continue and advance the alignment of national research activities that aim at charting the way towards a North Seas Offshore Network. More specifically, the key aspects of this objective are

- harnessing, sharing, and trading of offshore wind resources,
- supporting the utilisation of the offshore region's wind resources,
- making the national markets more efficient by increasing connection capacities, and
- providing balancing from Nordic hydropower in the North Seas.

2.2. Partners

Involving the nations adjacent to the North Seas, i.e. the North and Irish Sea, the NSON Initiative has a strong European focus to tackle the multiple challenges of an offshore grid development. For this purpose, R&D organisations from Norway, Denmark, Ireland, the Netherlands, the UK, and Germany complement each other's national research activities by international collaboration in the fields of grid technology, network planning and operation, as well as energy markets and system integration. All research partners have worked on projects related to these topics individually on a national arena and together in European projects.

3. Modelling stages in the German NSON project

With the goal of analysing and evaluating different concepts of a potential offshore grid in the North Seas region, the German NSON project (NSON-DE) investigates impacts on both the German and the overall European energy supply system. To this end, the project's core activities focus on four main areas to assess the feasibility and the implications of various NSON

concepts. The sequence of the corresponding modelling stages and their geographical focus are illustrated in Figure 1. As a distinguishing aspect, it has to be noted that these stages are strongly connected through consistent data sets, modelling assumptions, and feedback loops.

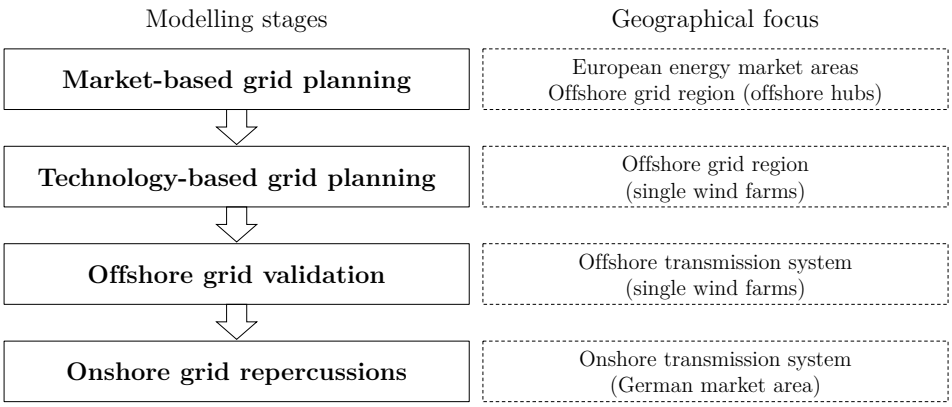

Figure 1. Modelling stages and their geographical focus in the NSON-DE project.

3.1. Market-based grid planning

The main goal of this first phase is to determine and assess market-driven investment decisions in a potential NSON, while adequately accounting for the directly and indirectly connected onshore market areas. Together with the underlying scenario information, this stage yields exchange capacities and energy flows between the offshore grid region and all relevant market areas, which serve as input for the subsequent technology-based grid planning stage.

Given the ambitious decarbonisation targets in Europe, it is vital to not ignore the potential interaction among energy sectors, i.e. power, heat, and transport, when carrying out technology assessments in future energy scenario settings [5]. The coupled operation of the sectors in multi-energy systems [6] can exhibit significant flexibility contributions in a future energy system.

Hence, in a first step, two energy scenarios for 2030 and 2050 were determined by running the SCOPE model, which has been developed at Fraunhofer IEE [7]. Minimising system operation and investment costs, while at the same time complying with a given carbon emission target covering all relevant sectors, this deterministic generation expansion planning model is formulated as a linear program (LP) for a full year discretised into 8760 consecutive hours. All time series data related to meteorological information, e.g. wind and solar production, thermal and cooling loads, etc., is based on COSMO-EU data [8].

In order to investigate long-term investments in potential offshore grid topologies, a market-based large-scale offshore grid transmission expansion planning model was developed with a particular focus on capturing future energy system flexibility in the onshore market areas. This requires aggregated modelling approaches for hydropower systems [9] and thermal power plants (integer clustering), as well as bi- or multivalent sector coupling technologies, e.g. [5]. Based on the linear cost model presented in [10] and a novel estimation of investment cost model parameters for VSC HVDC transmission technology in [11], the model also accounts for the important fixed cost components of offshore grid infrastructure, i.e. fixed converter and platform costs. Therefore, the overall optimisation problem is formulated as a mixed-integer linear program (MILP). Despite the aggregation efforts, a new decentralised solution approach based on regional and unit decomposition had to be developed to efficiently handle the hourly interactions of the key flexibility providers and the renewable generation when making investment decisions in offshore grid infrastructure.

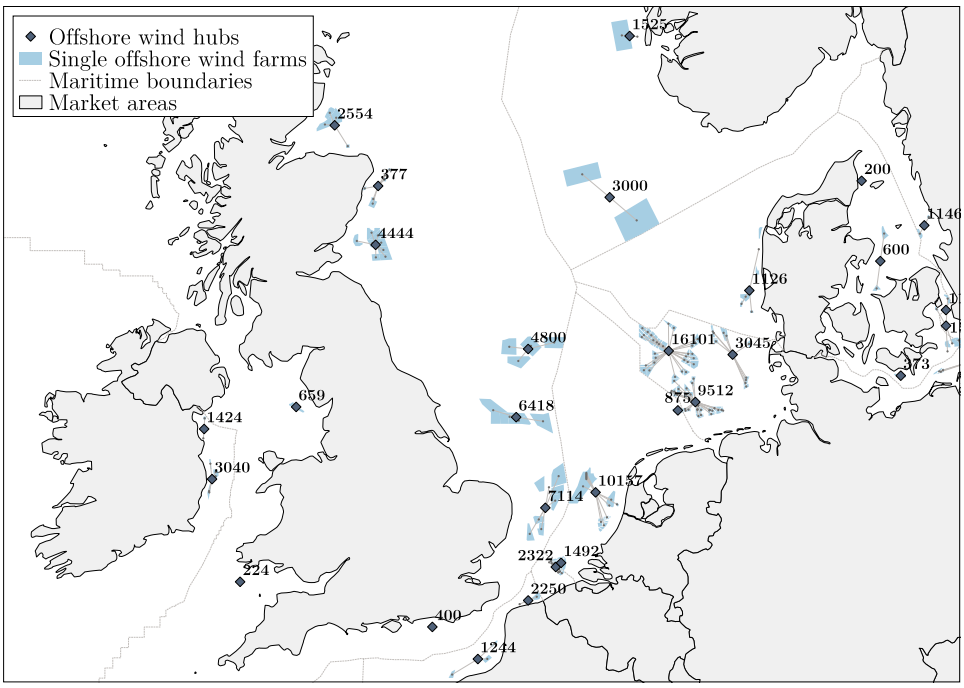

Figure 2. Single offshore wind farms based on [12] and clustered offshore wind hubs relevant for offshore grid investment decisions in the NSON 2050 scenario (values indicate installed generation capacity at offshore wind hubs in MW), own illustration based on [13].

To ensure consistency along both grid planning stages, the same database for offshore wind generation data is used. This means that structural and spatial information of single offshore wind farms, based on [12], is combined with site-specific wind generation profiles, based on the COSMO-EU weather model. While the market-based grid planning model needs to reduce the spatial resolution by aggregating offshore wind farms to so-called wind hubs for computational reasons, the technology-based grid planning stage considers the detailed granularity of single offshore wind farms. The offshore wind hubs, which are relevant for offshore grid investment decisions, are determined by a k-means clustering procedure in each market area's exclusive economic zone (EEZ), as illustrated in Figure 2. Some special wind farms, such as near-shore wind farms or small test turbines, are not explicitly considered for the offshore grid investments. Instead, the production of these wind farms is implicitly accounted for in the model. The final case studies investigate three topology paradigms for both the NSON 2030 and 2050 scenario:

- **Status Quo**, allowing radial offshore hub connections and no expansion on existing interconnector corridors,
- **Business as Usual**, allowing radial offshore hub connections and expansion on existing interconnector corridors, and
- **Meshed Grid**, allowing meshed offshore hub connections and expansion on existing interconnector corridors.

3.2. Technology-based grid planning

The market-based grid planning stage yields time series data of potential exchange capacities and energy exchange flows between the offshore region and the onshore market areas. In the subsequent technology-based grid planning stage, these exchange capacities and flows are considered as input and the spatial and technical configuration of the offshore grid is determined

by simultaneously optimising the locations of future wind farms, their connection(s) to shore, and the main technical components (i.e. transformers, converters, switches, platforms, AC lines, and DC lines). To that end, the main components of DC and AC transmission have been identified together with their technical parameters for different voltage levels and power classes. Since a long-term planning horizon until 2050 is considered, the problem is to find an incremental construction plan with operable intermediate stages for the grid. This problem is modelled as a MILP, whose integer variables describe the expansion and configuration decisions and whose continuous variables describe the power flows in expansion stage and scenario. Due to the enormous size of the model, the power flows are described only approximately by a transportation model that simplifies many physical effects.

The potential grid consists of nodes for wind farms and hubs, and of connections among them and the onshore grid connection points. For the nodes, the North Seas area is cast into a raster of 7 km $\times$ 7 km squares, for which potential power supply, investment, and operating costs are calculated. In addition, a coarser raster of hubs serving as AC or DC power hubs is added. Furthermore, all existing and planned offshore projects reported in [12] and shown in Figure 2 are taken into account by adding individual wind farms and hubs corresponding to these projects. Wind farms can be connected to shore directly, via the hubs, or both depending on the respective distances. Hubs can be connected to the shore and among each other both via AC and DC, depending on the distance and the length limitations of the respective technologies.

Due to the very detailed technical and spatial resolution of the model, it becomes computationally infeasible to consider time series with an hourly resolution over a full year for each of the intermediate expansion stages. Thus, a robust optimisation approach, solving the model only for a small subset of those snapshots from the time series that are crucial for the expansion, had to be developed. In order to identify these critical snapshots, a heuristic approach solving a simplified model in a repeated fashion has been devised.

Beyond that, newly developed heuristics are used to quickly compute feasible initial solutions and to construct feasible solutions from the information given by the LP solutions during the solution process. This reduces the time for finding feasible solutions enormously.

Eventually, it needs to be checked whether or not the offshore grid infrastructure computed in this stage with the simplified power flow model also permits real power flows that respect all physical effects. For this purpose, set points for the offshore grid components need to be determined for the complete time series. This is done by solving a capacity-constrained flow problem for the capacities determined in the grid expansion optimisation. The objective in this final step is to minimise the deviation from the desired power exchange values that have been determined in the market-based grid planning stage. The resulting set points and the optimised grid topology and configuration are then fed into the detailed power flow analysis of the next stage.

3.3. Offshore grid validation

Both offshore grid planning stages make simplifying assumptions to emulate the electrical behaviour of the different grid components. In other words, branches and nodes are used as grid components and their losses follow linear functions for computational reasons. Based on the market simulation results from Section 3.1, active power flows between the onshore market areas and the offshore grid are to be seen as approximations for calculating respective power flows within the grid to be built. In order to electrically validate the results of the grid planning algorithms and integrate the grid structure including its power flows between the now connected asynchronous AC systems, the optimisation results are tested using the power system analysis software application PowerFactory.

Because of ongoing changes, planning for multiple scenarios and time steps, an automated validation approach is chosen. Therefore, typical electrical models of the different offshore grid

Table 1. Comparison of exemplary power exchanges and losses in the offshore grid planning and verification stage in the test grid based on [14] - average over all 8760 time steps.

Type	Quantity	Planning		Verification		Difference	
		$\sum \lvert P^p \rvert$ in MW	$\sum P^p_{loss}$ in MW	$\sum \lvert P^v \rvert$ in MW	$\sum P^v_{loss}$ in MW	$\sum \lvert \Delta P^{p,v} \rvert$ in MW	$\lvert \sum \Delta P^{p,v}_{loss} \rvert$ in MW
Transformer	1	44.69	0.185	44.60	0.155	0.095	0.030
Line	41	9927.50	42.134	9612.77	18.798	1543.260	23.391
Converter	20	5850.19	58.502	5841.73	74.500	29.766	15.998
Onshore market area	4	4200.24	-	4222.66	-	41.948	-

components used in the grid planning stage were parameterised according to the assumptions made in the technology-based grid planning stage. The offshore grid itself consists of DC and AC components of the voltage levels 150, 300 and 500 $\mathrm{kV_{DC}}$ as well as 150, 220 and 400 $\mathrm{kV_{AC}}$. From the given components in the previous section, electrical models of transformers, converters, lines, and buses were used to create the overall offshore grid model. According to the electrical possibilities of transformers and converters, conversion between different voltage levels and technologies are possible and correspondingly created in the model. Since the previous planning stages are not concerned with the technical operation of the network, establishing feasible node types for the power flow in the grid (PQ, PV, SL) and combining them with the respective control structures of the converters ($\mathrm{U_{AC}}/\phi$, $\mathrm{U_{DC}}$/Q, P/Q) is one of the main challenges in this stage.

For verification purposes, the model was built and power flow calculations for every time step of an exemplary year (8760 h) and scenario were calculated. The resulting power flows and losses were automatically fed back together with the results of the optimised grid planning. Thus, assumptions and simplifications used for the power flows in the grid planning stages could be verified by the real power flow implementation.

Validating a test grid based on [14], Table 1 compares the cumulative planning with the corresponding verification results obtained from the detailed power flow calculations. It can be seen that the differences in power exchanges from and to the onshore market areas are well below 1 %. The main criterion of the technology-based grid planning stage is the fulfilment of trading demands and schedules, while only considering a very small number of time steps. Thus, achieving an accuracy of 1 % is a very promising result. The power flow deviations on the different lines (1543.26 MW) result from a different routing of the power flow in the validation compared to the assumed flows in the planning stage. However, the overall transmitted power is within a reasonable range of around 300 MW on average (9927.50 compared to 9612.77 MW). Losses tend to be overestimated for lines and underestimated for converters. This is due to the fact that only active power flow has been considered in the planning stage and further effects such as voltages different from nominal values, resulting in differing currents for a certain power transfer, have been neglected. In this context, further modifications are planned in order to achieve a higher accuracy also for the assumed losses.

3.4. Onshore grid repercussions

To investigate offshore grid repercussions in the onshore transmission system of the German market area, market simulation data for the NSON 2030 scenario from Section 3.1 and offshore grid planning data from Section 3.2 are combined with a detailed grid model representing the German part of the continental European transmission system. The resulting power exchange with the offshore grid at the onshore connection points are implemented in the onshore grid model together with detailed time series of generation and load patterns for all considered grid

nodes in Germany.

The German transmission grid data has been extracted using the data supplied in the German grid development plan for the year 2030, which was made available by the Bundesnetzagentur (German grid agency). Spatially and hourly resolved load and generation data for each grid node is provided by the SCOPE model and its input data, see Section 3.1 and [15]. Each of the following generation and load types is captured by individual and regionalised time series data in the grid model:

- **Renewable generation types**: onshore wind, offshore wind (i.e. offshore grid exchange), roof-top PV, utility-scale PV, flexible and inflexible biomass, waste, scrapwood, conventional and pumped hydro,
- **Thermal generation types**: extraction condensing units (CHP), back-pressure units (CHP), condensing units, gas turbines,
- **Traditional load types**: households, trade and services, industry, agriculture, public transport, pumped hydro,
- **Additional load types**: battery and plug-in hybrid electric vehicles, hybrid overhead-line trucks, industry heat pumps, decentralised air- and ground-source heat pumps, direct electric heating units (CHP and non-CHP), air-conditioning.

While the allocation of both generation and the traditional load types has mainly been established in previous projects, spatially distributing the additional load types required novel approaches. Moreover, the unit commitment configuration (MILP) of the SCOPE model employing a rolling optimisation horizon is used to simulate the power market in order to obtain unit-specific schedules, allowing for a detailed re-dispatch analysis.

By a combination of these sources, it is possible to analyse the impact of different market exchanges for the different offshore grid topology paradigms from Section 3.1.

4. Remaining challenges

Over the course of the NSON-DE project, a number of remaining challenges were identified and will be further discussed below.

4.1. Flexibility and uncertainty in future energy systems

Given the pursuit of long-term decarbonisation targets, future power systems face the task of integrating renewable power and providing flexible backup production capacity [9]. Adequate grid infrastructure such as an NSON with its twofold connection function of integrating offshore wind and facilitating power trade can contribute valuable flexibility in this context. At the same time, however, it competes with future onshore flexibility options, particularly those listed as additional load types in Section 3.4. These trade-offs become increasingly important and have to be incorporated in the transmission expansion planning tools analysing robust grid investment strategies.

Moreover, the uncertainty stemming from bottom-up developments and top-down target definitions needs to be represented in offshore grid investment decisions. This includes both strategic and operational uncertainties. Climate and energy targets constitute strategic uncertainties as do investment cost assumptions for VSC HVDC technology [10]. Further operational uncertainties are, for instance, introduced by an increasing interaction between the traditional power sector and other energy sectors: How building and industry heat or transport demands will be met by renewable production from wind and solar can be a crucial element in future power systems. As renewable generation from wind and solar predominantly exhibits capital expenditures, simultaneous optimisation of generation and transmission expansion for a highly decarbonised system heavily relying on those technologies is the natural next step.

4.2. Market integration and cost-benefit sharing

By connecting asynchronous zones and allowing electricity to flow according to price signals, a successful operation of an NSON requires harmonised cross-border rules of the involved market areas. To this end, various existing forward, day-ahead, intra-day, and balancing markets of Scandinavia, Great Britain, and continental Europe need to be made compatible with each other through harmonised operating timescales and market products. In addition, detecting and relieving grid congestion, both on- and offshore, are important tasks in integrated power markets which also demand new solutions.

As a multilateral NSON development in the form of integrated and hybrid transmission assets has been scarce so far, implications for cost-benefit distribution are essential aspects. A thorough understanding of how cost-benefit allocation and sharing methods can be applied to both directly and indirectly connected market areas is required. Of equal importance are potential conflicts between national, regional, and international goals in the development of offshore transmission infrastructure. Further research needs to focus on a possible framework under which common NSON investments could be secured with stakeholder's positions accommodated and crucial conflicts resolved.

4.3. Grid operation

The combined operation of large-scale AC/DC grid structures leads to new challenges and options in control strategies for all stakeholders in the overall system. In this context, a safe and secure system operation cannot solely be ensured by the single transmission system operators (TSO) individually operating their respective transmission grids. Instead, the operation task requires an overall picture of the combined grid, especially when it comes to further technical and economic optimisation of the system. Some of the main issues of a combined operation are discussed as static and dynamic aspects of hybrid AC/DC networks below.

From a static point of view, one vital aspect is an optimised grid and plant control of the combined AC/DC system. This includes the integration of DC systems in an optimised AC grid as well as joint AC/DC grid operation, requiring new optimisation algorithms incorporating the possibilities given by HVDC connections towards asynchronous systems and within the synchronous system, respectively. Together with new equipment, it becomes possible to control the power flow within the AC systems more effectively than before, e.g. by phase-shifting transformers, converter-based flexible AC transmission systems (FACTS) parallel to synchronous AC grids. Further increasing the power exchange between market areas for economic (minimisation of generation costs) or techno-economic reasons (e.g. shared/combined provision of system services such as control reserve powers) may also lead to an increased or even excessive use of the transfer capacities between the respective grids. Systematic positioning and operation of power flow regulating units could be one beneficial option to mitigate immoderate and costly grid extension.

From a dynamic perspective, new control concepts in normal and in fault/emergency situations of the grid and (selected) components are necessary. Regarding system services, dynamic control of frequency and voltage using HVDC systems as well as previously introduced components could enhance the security of supply and grid operation. Furthermore, an active contribution of large offshore wind farms to these system services needs to be further developed, integrated into grid operation, and made available to the respective operators. Future system restoration might also rely on novel features of renewable generation and HVDC systems if, in case of an emergency, conventional generation units are not committed through the market clearing process.

4.4. Grid planning

A major computational challenge in the NSON project was to efficiently solve the optimisation problems arising in the grid planning stages. The technical complexity and operational flexibility of the various transmission technologies, the large number of potential and actually involved network elements, the combination of different timescales, as well as the consideration of coupled markets and energy sectors lead to mathematical models which are extremely large and hard to solve. Even after several stages of simplification and aggregation, specialised solution methods combining decomposition, adaptive model refinement, and specially tailored heuristics are required to solve the models arising from the considered (sub-) problems.

One of the main challenges stems from the combination of very different timescales in the optimisation: Planning horizons of several decades are required to model strategic network expansion decisions, while time series with 1 h resolution are required to model the flexibility of power flows in the network. Choosing an appropriate subset of snapshots from these time series is a valid approach to ensure the computation of a robust grid network. In order to adequately describe and assess the effects of power storage technologies and of the increased flexibility of modern grid operation technologies, however, it is necessary to consider complete time series instead of individual snapshots. The development of new modelling and solution approaches, handling time series data computationally more efficiently, remains a very interesting and challenging field for future research.

Furthermore, several physical effects related to power flows and power losses are simplified in the optimisation models and only verified in the subsequent grid validation stage. Although the results of the verification have been satisfactory in most cases, the development of more accurate but computationally tractable simplified power flow and power loss models, as well as the development of adaptive model simplification and refinement techniques to be used in the grid optimisation remain an important field of research.

Another great remaining challenge is to develop and incorporate approaches to handle statistically known data uncertainties or barely predictable political, technological, or economic uncertainties in a computationally valid way in the grid planning. Given the size and the complexity of the underlying deterministic optimisation models, it is computationally prohibitive to use the current standard codes for robust or stochastic optimisation.

Finally, the available flexibility in grid operation (Section 4.3) has a big influence on the planning aspects of AC and DC grids. Incorporating the advanced flexibility of modern power flow regulation components leads to enhanced options and requirements in the grid planning stage. Thus, the positioning of the respective elements within synchronous or between asynchronous systems and their operation has to be considered in the planning processes.

4.5. Power Link Islands

A novel infrastructure design towards the integration of offshore wind resources located far out at sea is the idea of a Power Link Island (PLI) [16]. A PLI is an artificial island for transnational power exchange and distribution of offshore wind resources, while at the same time hosting other services such as operation and maintenance for offshore wind farms. Avoiding the construction of multiple individual HVDC connection systems with expensive offshore platforms, offshore wind farms could be connected via AC technology to the PLI. By building HVDC cables to participating North Seas market areas, the PLI could, therefore, facilitate both the transport of offshore wind generation and power trade between market areas [17].

However, the high uncertainty associated with the investment costs and potential locations, e.g. Dogger bank, of such an artificial island is a major challenge in this context. When pursuing the PLI as a medium- to long-term solution, potential investments need to be weighed against onshore flexibility options, see Section 4.1. Further, more sophisticated investment analysis models and tools are required, as the existing ones lack the possibility for a combined assessment

of the investment costs and the economic benefits a PLI offers in terms of other activities such as construction, maintenance, and service.

5. Conclusion

As part of the international NSON Initiative, the national NSON project in Germany (NSON-DE) investigates several aspects of future offshore grid deployment in the North Seas region. Focusing on different but consistent levels of technological and spatial granularity, a model chain has been developed to investigate long-term offshore grid development in energy scenarios with a high level of decarbonisation. As an extensive database was gathered and the tools can be easily customised, the model chain or single stages of it can now be used for in-depth case studies to support decision making. One interesting application could be the deployment of Power Link Islands in medium- to long-term scenario settings with a significant interaction between energy sectors to achieve the 2050 climate goals formulated in the Paris Agreement (COP21).

Acknowledgments

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