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Transmission expansion simulation for the European Northern Seas offshore grid

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ABSTRACT

HVDC innovations and the integration of power markets and renewables drive the development of a European Northern Seas offshore grid. This power transmission system performs two functions: interconnecting Northern European onshore power systems, and connecting offshore wind farms. Despite its benefits, the development of an integrated offshore grid combining the two functions is slow. The main reasons are the lack of cooperation and governance frameworks to overcome regional differences and distribute costs and benefits. These barriers were studied so far only qualitatively or through perfect foresight optimization models. We complement this by studying transmission expansion pathways of the grid, which are non-optimal and path dependent, using a novel and open-source simulation model for offshore transmission investments. Different expansion typologies are considered, which we find perform the grid functions with different levels of integration and transmission capacities. Besides these typology factors, modelling and simulation factors also affect the expansion selection. Typology, modelling and simulation factors interact to result in radically different offshore grid pathways, which exhibit strong path dependence. Thus, to avoid locking-out beneficial expansions for the Northern Seas offshore grid, planning should be regional and consider HVDC innovations. Then individual projects can be implemented based on their own merits.

1. Introduction

Our aim is to study the Northern Seas offshore grid, in order to understand which factors affect its expansion and make recommendations for expansion planning governance in Europe. We develop a transmission investment simulation model using myopic optimization, while previously quantitative studies on the offshore grid have applied mainly perfect foresight optimization. Our simulation approach demonstrates the strong influence of path dependence on the grid expansion, a factor which previous studies did not address. However, our model does not recommend a particular expansion plan, which would require a more detailed modelling of the system. In the introduction we present the offshore grid, its relation to the European power system and policies, and the current state of research, governance initiatives and development projects on the grid. We then argue for our simulation approach.

An offshore grid has two functions: the interconnection of onshore power systems through interconnectors, and the connection of offshore power generation technologies, usually wind power [1]. An integrated grid has transmission links that combine these functions to some degree, instead of each link performing only one. In early 2016 members of the European Parliament made an appeal to “realise the full potential of the Northern Seas energy system” through increased cooperation of countries in the region. Their manifesto emphasized the benefits of an integrated offshore power grid to the European energy system [2].

The Energy Union is the main strategy of the European Commission to address European energy challenges. The integration of the internal energy market is one of the five priority dimensions of the Union, and offshore electricity interconnectors and the (possibly integrated) Northern Seas grid are important elements to this dimension [2,3]. Other drivers for the grid comprise innovation in high-voltage direct current (HVDC) transmission, offshore wind

Abbreviations: AC/DC, alternating-current/direct-current; BI, British Isles; CE, Continental Europe; IC, interconnector; HVAC, high-voltage alternating-current; HVDC, high-voltage direct-current; NPV_a, absolute net present value; NPV_r, net present value ratio; PV, photovoltaic; SC, Scandinavia; TEP, transmission expansion planning.

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power development in the Northern Seas, and guaranteeing the reliability of European power systems [1,4,5]. However, despite these drivers and several studies and projects, the development of the offshore grid and especially its integration is slow [6–8]. Not surprisingly then, the manifesto of the members of the European Parliament [2] highlighted the need for regional cooperation and anticipatory investments ("leaving opportunities to upgrade cables at a later stage") for an integrated grid development.

Transmission expansion planning (TEP) is the field that studies how to best develop transmission grids according to preferred criteria [9]. Traditional TEP approaches use optimization or heuristics and face many difficulties. These include the increasing participation of renewables, decentralized and uncertain markets with multiple decision-making actors, conflicting objectives, large-scale generation projects, long permitting times, and regional integration [10]. Nonetheless, studies on European transmission such as the e-Highway 2050 project [11] remain confined to using optimization.

Optimization models provide normative guidance on the grid (that is, how it should develop), and several studies applied optimization to the offshore grid [1]. However, due to the slow development of an integrated grid, approaches to explore non-optimal scenarios and understand this slowness are also needed. Simulation is such an exploratory method, but has been rarely applied to TEP and never to the offshore grid. Scarce examples of TEP simulation include the use of game theory by Yen et al. [12] and Contreras et al. [13], of agent-based modelling by van Blijswijk and de Vries [14], and of system dynamics by Ojeda et al. [15] and Ochoa et al. [16].

Thus we employ simulation to study the transmission expansion pathways of the grid, i.e. its possible development in time. Our novel open-source model conducts myopic optimization in transmission investments [17]. The model is myopic (or short-sighted) because it has a restricted investment horizon of one period, as opposed to a perfect foresight optimization model which considers the whole time horizon. A myopic horizon leads to a non-optimal simulation of the grid expansion, which allows us to explore alternative pathways. This simulation approach allows us to represent the grid path dependence, where the previous state of the grid locks-in or restricts the expansion into certain pathways, unless external influences change the pathway. Therefore, our approach addresses both the non-optimality and the path dependence of grid expansion pathways.

Many governance initiatives, research, and generation and transmission projects on the Northern Seas grid are ongoing. The most recent and important governance initiative is the aforementioned Energy Union, which includes several proposals for the European grid. These comprise minimum interconnection targets for Member States, the establishment of further projects of common interest (PCI), guidelines on regional cooperation on infrastructure, and a revised market integration framework. Hence, the proposal from the European Commission and contributions from other energy analysts address financing, governance, top-down and bottom-up policies, and regulation [18–20].

As for projects, the main ones related to the offshore grid are national wind farm clusters and international wind farms (notably Kriegers Flak), and interconnectors between European countries. At least 15 interconnectors in the Northern Seas were in various development stages in 2015 [4,21]. Of those, three combine the onshore systems interconnection and the offshore farm connection functions indicated above.

Finally, on-going and concluded research projects on the offshore grid cover legal, economic, technical and regulatory aspects of the grid. Results indicate an integrated grid approach can provide investment and operational savings and lower environmental impacts, contribute to security of supply, and advance European marine governance [1,8].

Despite these advances, the Northern Seas offshore grid still faces barriers as mentioned, especially for typologies which integrate the two grid functions of connection and interconnection. The fundamental reasons indicated in the literature are the lack of cooperation and governance frameworks to overcome regional differences and the distribution of costs and benefits at the national and actor levels. To Jay and Toonen [8] collaboration has progressed but is still slow and limited, both among member states and of these with industry. It is hampered by regulatory complexity and misalignment, project difficulties, soft legal approaches at the European level, and the lack of involvement of civil society. Fitch-Roy [6] on its turn sees an increased convergence among countries in models for developing offshore wind farms, with a mixed contribution of the European Union to this convergence process. Nonetheless, this convergence is not necessarily reflected in an effective cooperation for grid development. Flynn [7] highlights the weight of the national level and national differences in the development of renewables, as opposed to the European level. The author sees a stark contrast between ambitious visions for an integrated grid and the reality of interconnection and offshore wind being a national or bilateral matter. Hence, the development of interconnection in Europe is challenged by factors that go beyond interconnection economics, and involve governance, preferences and cost and benefit perceptions of actors, and politics. This agrees with Puka and Szulecki [22], who highlight the current primacy of governance and political issues over finance and economics in the development of European interconnectors.

In summary, although an integrated grid provides significant benefits to countries and actors, its development is delayed by various barriers. Given its importance, it has received the attention of numerous research projects using mostly qualitative or perfect foresight optimization approaches, which contributed to understanding the benefits of an optimal grid design [1]. But despite the consensus that the actual grid development will combine both separate and integrated characteristics gradually, there is little research on how such a grid development could be [1]. Moreover, the existing planning governance frameworks do not mandate an integrated planning of the offshore grid, meaning neither do the network planning practices of ENTSO-E.

By conducting TEP with simulation we provide researchers with an alternative methodology to the ones frequently applied to study grid pathways. By studying transmission expansion pathways for the offshore grid this article demonstrates factors that affect the pathways and their path dependence, and elaborates on the consequences to planning of the grid. Also, a future application of the methodology with a more detailed modelling of the European power system can support the development of specific expansion plans of the offshore grid, complementing conventional TEP approaches.

This article is organized as follows. Section 2 presents the simulation approach to energy systems modelling, with a theory on the change of transmission infrastructures through investment, and then Section 3 presents the offshore grid model. The case studies, results and discussion are presented in Section 4, and finally Section 5 concludes with the consequences to the expansion planning governance of the Northern Seas offshore grid within the Energy Union.

2. Transmission expansion planning and pathways

Here we introduce simulation within the context of energy systems modelling and present the framework to model transmission investments, arguing that investments determine the