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# A Review of the North Seas Offshore Grid Modelling: Current and Future Research

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## Abstract

The North Seas offshore grid serves to connect offshore wind power to onshore systems, and to interconnect power systems in Northern Europe. Its development is a priority for the European climate and energy policy, which has led to a number of studies on the subject. Nonetheless, research questions, assumptions and typologies can vary considerably among them, and thus to guide future research this paper reviews the published works that use bottom-up energy models. This review develops a simple and effective methodology that can be applied to other reviews of energy systems models. It jointly considers the studies of interest, the system characteristics, a categorization framework and relevant indicators. The analysis indicates most studies focus on investment and operation of the grid using optimization models, with rare use of other research questions or other model approaches. Moreover, results vary significantly, and their comparability is limited due to differences in assumptions, methodology and detail of results publication. Nonetheless, integrated typologies frequently present economic, operational and environmental benefits, although the reviewed studies do not unambiguously warrant immediate and full cooperation on grid governance. Lastly, future research should be attentive to the presentation and resolution of data, assumptions and results, as well as consider grid characteristics relevant to the research questions.

*Keywords: North Seas; offshore grid; offshore wind; transmission expansion; power system; energy modelling.*

## 1. Introduction

Saying that the power sector is complicated is an understatement. It comprises multiple technologies, actors and institutions interacting among themselves and with other systems, which certainly does not make the life of the energy analyst easy - nor uninteresting. Furthermore, many power systems have gone through technical and institutional change in the last decades, and face further ones due to the energy transition. An interesting case is Europe, where the North Seas offshore grid (NSOG) will play a leading role in the transition of its power system. The NSOG is an offshore high-voltage transmission system connecting offshore wind power (OWP) and onshore power systems in the North Seas. It is composed of transmission assets (interconnectors and generation connectors), without a predefined transmission technology or topology of the grid, that is, on the connection pattern of the assets. Although some of these transmission assets already exist, it is expected future development will significantly alter the typology of the grid (the combination of a topology and technologies). In this future typology the offshore grid can be one of the world's first supergrids, large and long-distance transmission networks which enable transitions in energy systems. Besides these technical components, the NSOG also comprises a social sub-system with many actors, their networks and the institutions influencing their behavior.

*Abbreviations*: CCGT, combined cycle gas turbine; CSC, current source converter; HVDC, high-voltage direct-current; HVAC, high-voltage alternated-current; NSOG, North Seas offshore grid; TEP, transmission expansion planning; TYNDP, ten-year network development plan; OWP, offshore wind power; RES, renewable energy sources; VSC, voltage source converter

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This review addresses the recently published (from 2010 on) studies on the offshore grid, limiting itself to bottom-up approaches. These more adequately address the features of the NSOG and are thus commonly employed in its modelling. It reviews studies results, compares their differences and presents indicators, and relates the studies to the characteristics of the offshore grid. Furthermore, this review contributes a simple but effective methodology for analyzing energy systems models according to the characteristics of the system in question. Finally, the framework of offshore grid characteristics developed is useful for researching this grid as a system.

The North Seas offshore grid is a priority corridor for the European Commission (EC) and will contribute to the 2030 Climate and Energy Policy framework goals, to the completion of the Internal Energy Market and to technological and industrial policy goals [1]. The 2020 climate and energy package established a binding target for renewable energy in each Member State final energy consumption. Complementarily, a secondary goal of the 2030 Climate and Energy Policy Framework is to take renewable energy to 27% of energy consumption, and to achieve EU pledges the power sector must reach almost complete decarbonization by 2050 [2]. With the promotion of competition and security of supply, these are the pillars of European energy policy driving offshore wind, and broadly renewable power. However, the lack of 2030 binding targets at a national or sectorial level and the necessity of specific support schemes for renewable energy are still a subject of debate, the latter being summarized by EEG [3].

Despite these drivers having a European aspect, offshore wind development has occurred so far at a national level, as the offshore wind trends presented by Rodrigues et al. [4] indicate. Over 8 GW of capacity was installed in Europe by 2014, and was forecasted to reach 10.9 GW by the end of 2016 [5]. De Decker and Woyte [6] list technical progress and development of OWP and interconnectors as the main drivers affecting the NSOG, which will concur to give OWP development an increasingly European perspective. It is relevant to note that the North Seas are considered to be the Irish, North and Baltic seas, the English Channel and Kattegat and Skagerrak.

Independently of its typology, the NSOG serves two functions: connecting offshore generation to onshore power systems (the connection function), and interconnecting different power systems (the interconnection function). Through those, it can develop offshore power generation, interconnect power markets, increase reliability, reduce $CO_2$ emissions, and promote technological and industrial policy goals. While the NSOG can in the future connect other renewable energy sources (RES) of electricity such as tidal or wave, wind will be the main one for the offshore grid. Spro et al. [7] also indicate supplying power to offshore facilities and connecting deep-water energy storage as benefits. Nonetheless, these are unlikely to be the as relevant as the main functions of the grid, even in the long term.

Several research projects in the last years studied the NSOG, such as OffshoreGrid, North Sea Transnational Grid or the collaboration between E3G and Imperial College [8–10]. Despite these, there is still uncertainty on the NSOG pathway and the most adequate policies and market designs for it. The offshore grid requires the use of different methodologies to address different research questions, and a large number of studies have been published due to its importance to European goals. Thus, these studies use diverse approaches, which make their comparison and validation challenging. As a consequence, to review the models is to address a relevant but complicated area of energy systems modelling. In this way, readers interested in modelling theory, transmission expansion or energy policy will find contributions to those in this review.

Energy systems models are usually classified by approach (top-down or bottom-up) and method (optimization, equilibrium or simulation), although other classifications are possible [11–13]. On the one hand, top-down models address whole economic sectors and their interaction using aggregated high-level indicators. On the other, bottom-up approach models sectors in detail, considering specific features such as technologies and costs. Thus, top-down models account for feedback between different sectors but are unable to represent any given sector in detail, whereas bottom-up models capture those details at the cost of ignoring feedbacks in a broader system. Hence, it is not surprising that to the authors' best knowledge all models currently developed for the NSOG are bottom-up models, which are thus the focus of this review. The disadvantages of the bottom-up and top-down approaches did lead to the advocacy of hybrid models. These models combine top-down approaches with detailed representation of some sectors to capture both feedbacks and system features of interest, at the cost of increased model complexity. However, this review did not find studies using hybrid models that study the NSOG specifically.

The rest of this paper is organized as follows. Recent developments concerning the grid and a summary are presented next in this section, while the second section presents the methodology of the review. Then, the third section reviews the bottom-up modelling studies according to the categorization framework, the relevant indicators and the characteristics of the offshore grid. Finally, the conclusion summarizes the main findings of the review and presents recommendations for future work on the offshore grid.

### 1.1. Recent Developments

It is not only wind power that is currently developed mostly at a national level. Despite the potential coordination benefits, offshore interconnection and connection investment in Europe is also led nationally. Interconnector development is conducted bilaterally by national Transmission System Operators (TSOs), or by other companies in the rare case of merchant interconnectors. Since 2010 the ENTSO-E publishes the Ten Year Network Development Plan (TYNDP). Nonetheless, mechanisms to promote international transmission investments are still limited to the Projects of Common Interest (PCIs) and the Connecting Europe Facility (CEF). In addition, the ENTSO-E [14] indicates that the CEF is only for projects that are "commercially not viable", and that it is insufficient for the funding needs of TSOs. In early 2015 the EC published the Energy Union plans. These include a 2nd list of PCIs, an energy infrastructure forum, the European Fund for Strategic Investments and a review of the electricity regulatory frameworks [15]. Increased regional cooperation is an important strategy for the Energy Union, with the EC aiming the transfer of responsibilities on the energy mix from a national to a regional level [16].

E3G [17] identifies thirteen active interconnector projects and three integrated connection-interconnection projects in the North Seas for a total capacity of 14 GW. Of those, twelve projects are in early phases, and four in advanced phases of commissioning, permitting or final investment decision. However, this picture can change significantly and fast, as exemplified by advances in other two interconnectors as follows. Dutch and Danish transmission system operators committed in 2014 to develop the COBRA cable, while a final investment decision was expected for the NSN link between the UK and Norway. Moreover, delays to interconnection projects can be just as common, thus affecting the NSOG pathway.

Besides interconnector development, connection regulation is another important factor for the NSOG pathway, given the relevance of this function. Currently, Belgium, Denmark, France Germany, Ireland, the Netherlands and Norway adopt what Meeus [18] calls the TSO regulatory model for the connection of wind farms to shore. On the other hand, the UK uses the so-called third party model and Sweden the generator model, where the name indicates the wind farm connection responsible party. Additionally, Sinclair Knight Merz [19] states that shared transmission assets for connection (creating OWP hubs) is possible in Germany, given its regulation. Finally, in 2014 Belgium and the Netherlands have approved the

TSO model for offshore wind shared connection to shore [20,21]. This exemplifies the differences in regulation among European countries.

In summary, the offshore grid is driven by external factors and contributes to multiple European goals, and investment mechanisms and regulatory possibilities exist for multi-party development of connectors and interconnectors. Despite that, these are limited and so far have not fostered it in a significant scale. Moreover, recent events indicate these will continue to be conducted nationally or bilaterally in the short-term. Additionally, any integration benefits of the NSOG must be evaluated against relevant technical, environmental and socio-economic costs, which may be difficult to assess appropriately. For example, the NSOG promotes transmission flexibility, but by doing so it may connect hydro storage capacity resulting in a complex interaction of transmission and supply flexibility. Given the number and diversity of approaches, this analysis provides recommendations to future research by reviewing the recently published bottom-up modelling grid studies.

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## 2. Methods

The review of the NSOG bottom-up energy models uses a 3-part framework, which is then applied to the analysis. These frameworks consist of characterizing power systems and the NSOG, developing categories for the review and then relevant indicators, as indicated in Figure 1. The characterization is necessary due to the complexity of the NSOG, while categories and indicators allow applying best practices from previous reviews, and exploring common data between the reviewed studies. The six characteristics classes listed in Figure 1 influence the energy model choice and are discussed in detail in this section. The review categories allow to compare the offshore grid studies, and are also presented here, while the indicators are directly presented in the results section.

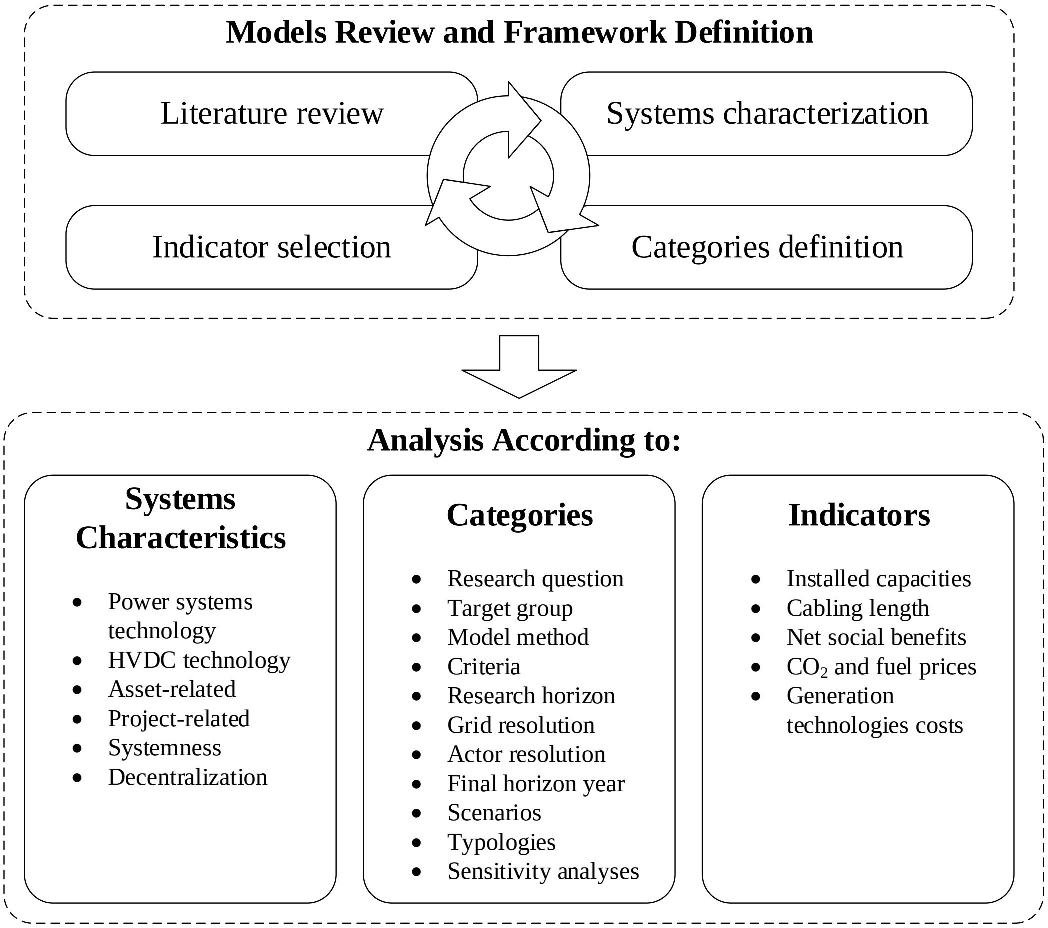

**Figure 1: North Seas offshore grid review methodology.**

The characteristics of the NSOG, and of transmission systems in general, allow to classify it as a complex system. That is, a defined set of interdependent elements with specified functions, boundaries and interaction rules, whose representation depends on the viewpoint and cannot include all the systems features single-handedly. Thus, conducting relevant studies on the NSOG requires considering its characteristics, choosing an adequate model and assumptions according to the research question, and justifying those explicitly.

Van Dam et al. [22] and De Vries [23] adopt different models for the subsystems of the electricity infrastructure, with social or economic ones respectively. Regardless of this, the social or economic subsystem still commands the technical one, and is constrained by it. With diverse system representations possible, the review methodology needs to consider the characteristics of electricity markets, transmission systems and the offshore grid from these socio-economic and technical perspectives.

## 2.1. Systems Characterization

### 2.1.1. Restructured Electricity Markets

For some decades now several electricity markets worldwide have been restructured (a process often referred to as deregulation, reregulation or liberalization). This consists in a shift away from centralized investment planning and operation to market-based decentralized decision-making with multiple actors, as described by Pérez-Arriaga [24]. These new market designs usually involve the institution of a regulator and a power exchange, and the establishment of markets for generation and supply activities. Also, it requires the unbundling of transmission and distribution, and their regulation as natural monopolies, with the definition of a system and a transmission operator (often the same agent). However, decentralization can leads to many challenges, including guaranteeing adequate and coordinated investment in transmission and generation, and coordination with energy, environmental and industrial policies.

In 2014 the day-ahead markets on the North Seas borders were coupled as detailed by EPEX [25]. Despite this, completing the Internal Energy Market still requires the implementation of many features of the European Electricity Target Model, which defines a vision for the harmonization of regulation. A major remaining feature is the integration of intraday, balancing and long-term capacity markets [26]. The offshore grid interacts with these ongoing developments, which shape how the grid performs its interconnection and connection functions, and how it evolves. Furthermore, regulation is a continuous activity whose focus can change in time. E.g. at the beginning of decentralization, the establishment of functioning power markets and regulation of natural monopolies were paramount, but since then the energy transition became one of the most important dimensions. Likewise, this shift has brought attention to the development of the NSOG, in order to promote European goals.

### 2.1.2. Transmission Systems

Since our focus is the NSOG, only a review of the general characteristics of transmission systems expansion is presented. Transmission Expansion Planning (TEP) is an important activity for power systems, and Pérez-Arriaga [24] provides a brief introduction to TEP while Latorre et al. [27] review the state of the art. It involves evaluating and authorizing transmission assets in a portfolio according to specified set of criteria (e.g. reliability and economic costs and benefits), and then establishing indicative or prescriptive expansion plans and execution responsibility.

If expansion planning is challenging, restructured electricity markets and the specific characteristics of the NSOG make its development from this perspective even more so. The pathway of the offshore grid is important not only to the investment perspective but also to its operation, since a given grid state depends on its pathway. Thus, the review of grid studies should also consider their contributions to expansion planning of the NSOG and relate it to current practices.

According to Latorre et al. [27], "the theory and tools for transmission planning are still below the practical requirements of the new power markets". Moreover, von Hirschhausen [28] states that for supergrids "surprisingly little attention has been given to long-term planning mechanisms, a critical element in such complex projects". A complementary observation is that TEP methodologies make little use of simulation models, using mainly optimization, heuristics or meta-heuristics in order to support planning decisions. The literature indicates therefore that there is potential for improving expansion planning practices for the offshore grid, whose main characteristics are reviewed next.

### 2.1.3. The North Seas Offshore Grid

The offshore grid characteristics can be classified in three main classes: technology, implementation and system. These main classes are further divided in two sub-classes each, as indicated in Figure 2. While some of these characteristics are common to all power systems, some are specific to the North Seas grid. Regardless, energy modelers musts consider which characteristics are relevant to their research questions and must be included in the modelling of the offshore grid. Thus, the characteristics are presented in detail next.

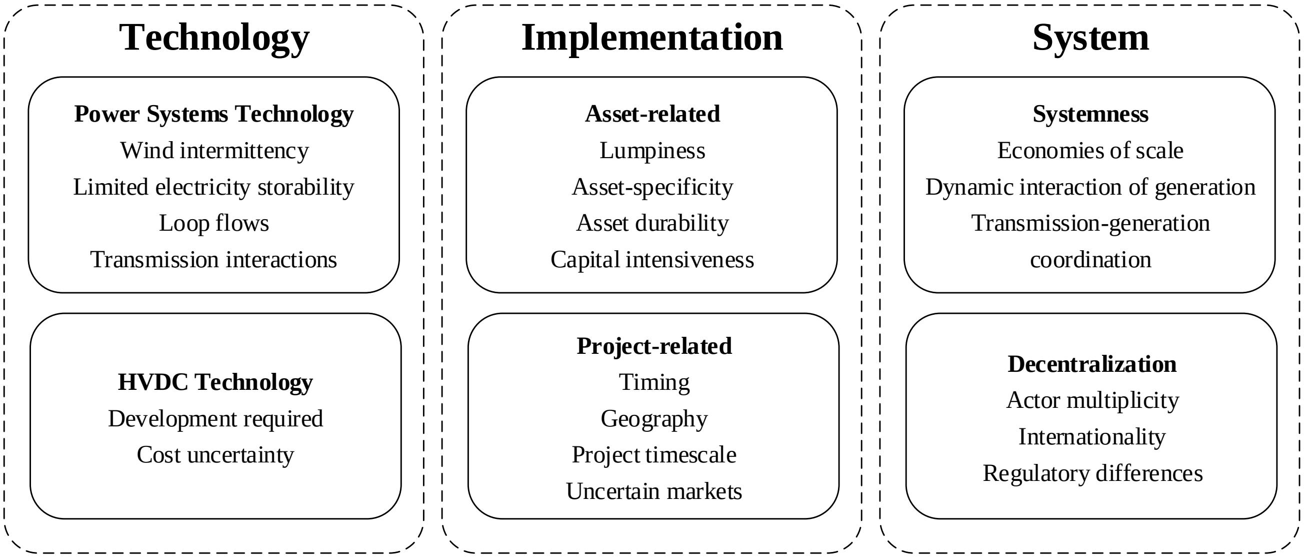

**Figure 2: North seas offshore grid characteristics.**

#### 2.1.3.1. Technology Characteristics: Power Systems and HVDC

Concerning power systems characteristics, compared to conventional power systems wind power is both more *variable* (presenting significant uncontrollable production level changes) and more *uncertain*, i.e. these changes configure a stochastic process [29]. Since wind marginal costs are low, the variability affects the dispatch merit order (the order on which generation technologies are dispatched). Also, the uncertainty of wind power increases imbalances in the intraday and balancing markets, and may require increased system flexibility to cope with those imbalances [29]. Furthermore, current *electricity storage technologies* are either incipient or have limited resource availability (e.g. pumped hydro storage). As for any transmission system, flows in parallel paths called *loop flows* restrict transmission capacity and may actually be worsened by additional lines.

As for HVDC technology, ENTSO-E [30] presents a previous review of offshore transmission technologies, while Grasselli, Quacquarelli, and Gentili [31] provide a more recent reference. In summary, *interconnector and connector technologies* available are high-voltage AC (HVAC), current source converters (CSC) HVDC and voltage source converters (VSC) HVDC. For shorter distances, HVAC transmission is optimal, after which HVDC is the preferred choice due to the increasing reactive power required by the high-capacitance HVAC cables. Specifically, VSC will be the preferred technology for integrated grids, since for longer transmission distances it has cost, controllability and integration advantages over both HVAC and CSC HVDC. However, aspects of VSC for a multi-terminal grid are still unproven commercially, especially large DC breakers, control strategies and interoperability between manufacturers (ENTSO-E 2012). Even though development risks are perceived as low by academia and industry actors, they still add uncertainty to investment and operation of a future grid.

#### 2.1.3.2. Implementation Characteristics: Asset- and Project-Related

Transmission system assets are discrete, capital-intensive (expensive) and durable, with lifetimes above 30 years, and thus transmission expansion is *lumpy and asset-specific* [24]. Then, the optimal technology and grid topology for an offshore interconnector or wind farm connection depends on *timing, project timescale, geographic disposition and costs* [30,32,33]. Timing is crucial since the longer the lead time between the implementation of two or more offshore projects, the higher the risk to the first one. This because of stranded investments, where if the second project is cancelled the first one bears all the costs and loses any integration benefit. This relates to the timescale of projects (its implementation duration), since projects of long implementation are riskier, increase the generation-transmission lead-lag issues described below, and thus affect the risk of stranded investments. Wind power and interconnectors in the North Seas will also connect to *markets with uncertainties* such as fuel and $CO_2$ prices, adding to project risk.

#### 2.1.3.3. System Characteristics: Systemness and Decentralization

Systemness is “the systemic character a sector exhibits” [34]. Firstly, the systemness of transmission systems create *economies of scale*, who do not level out as in generation [24]. Secondly, transmission and generation projects ideally should be *coordinated but have different timescales*, so transmission expansion can lead or lag generation [23]. Whether lead or lag is prevalent depends on technological and socio-economic aspects. In recent decades transmission expansion is increasingly lagging in Europe due to technical (faster deployment of generation) and social aspects (slower permitting and licensing of transmission projects). Finally, *different generation technologies* affect each other in the market, so offshore wind and onshore generation development interact.

Despite this systemness, the concept of the offshore grid is *independent of its technologies and its typologies*, which can range from less to greater integration of assets. This range of possibilities is illustrated in Figure 3, where integration and systemness increase from the radial to the integrated typologies. Indeed, several studies such as De Decker and Kreutzkamp [8], Egerer et al. [35] and Lévêque et al. [36] indicate the still incipient trans-European coordination of transmission expansion. To them, the offshore grid will be a mix of coordinated and uncoordinated developments, with a gradual increase of the former. However, there is not a consensus on implementing a *governance scheme* for the North Seas grid. Thus, Roeben [37] argues the existing legal framework is sufficient, while Woolley [38] and more recently Gaventa et al. [39] have called for a governance legal framework. On his part, Flynn [40] highlights the *ambiguity of drivers for the grid*. This because support at the European level conflict with difficulties in regional cooperation and system integration, cost reduction and the national character of financing and offshore wind and transmission development. One can expect then the actual offshore grid to be a combination of the Figure 3 typologies.

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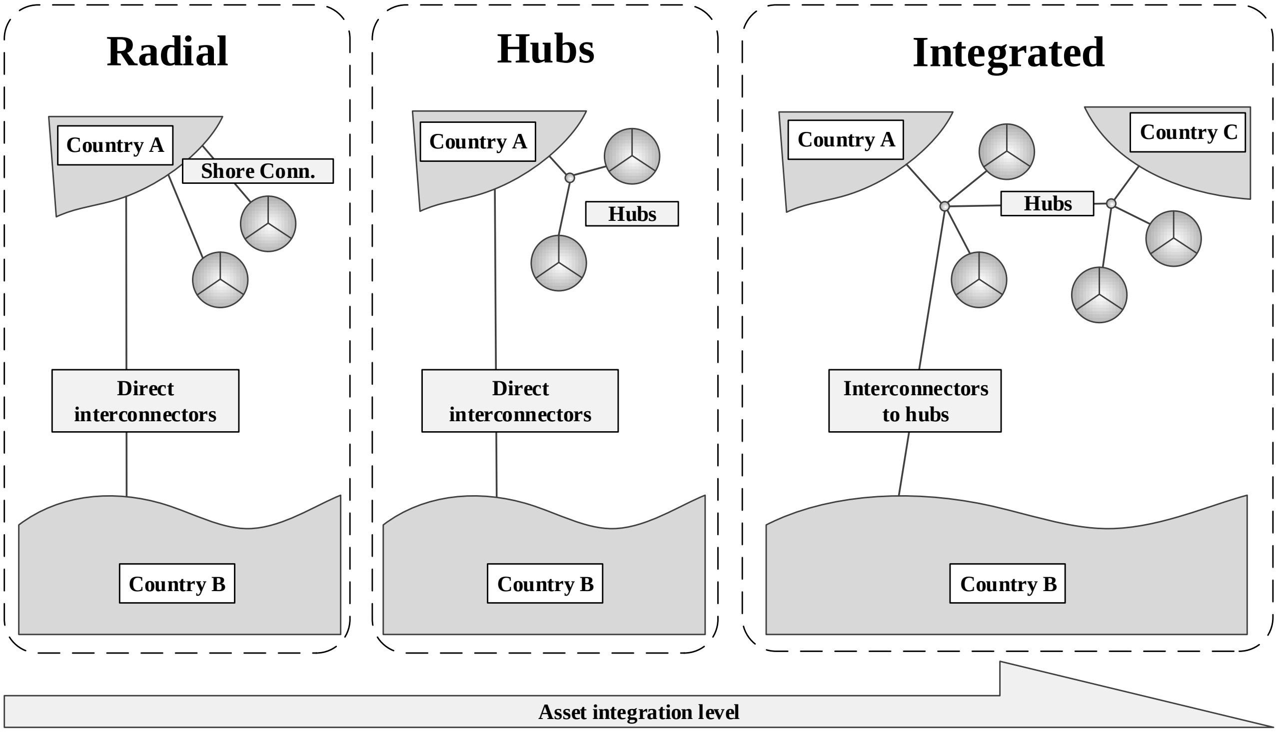

**Figure 3: Transmission typologies examples**

The next paragraphs cover decentralization, a crucial characteristic class since the NSOG involves European countries and actors with *different policies and regulations* that affect offshore wind power and transmission. Each difference needs to be considered for harmonization or at least compatibilization, but there is no consensus on the necessary level, as the conflicting conclusions of Wooley [38], Meeus [18], Flynn [40], Müller [41] and Piria and Zavolas [42] indicate.

The *classification and ownership of transmission assets* impacts who can develop transmission projects and to which rules these are subject, e.g. if connectors are part of wind farms, and if 3rd party interconnector access is obligatory. This is especially relevant to assets performing both connection and interconnection functions, since it affects responsibilities for investment and the typology of the assets.

*Transmission expansion and maritime spatial planning* is currently a national responsibility (with the ENTSO-E's ten-year plan being indicative). This results in differences in national approaches to interconnector development and wind farm siting and connection. Regarding the latter, the main difference is the existence of allocated hubs and cost allocation rules for connections. These issues also affect the possibility of shared transmission projects (even nationally), and of wind farms linking to interconnectors.

Meeus [18] indicates that *connection models* (the connection responsibility and cost allocation) should follow the principles of advanced connection planning, adequate price signals and a minimum of competition. Of the currently existing models, none can comply with all three principles, and thus harmonization or compatibilization has to deal with models that are imperfect even at a national level. *Transmission tariffs* are closely related to connection costs, and should be considered simultaneously when analyzing cost allocation and locational signals for OWP. However, despite zonal or uniform pricing being the European standard, differences remain in national approaches.

Many studies have addressed the issue of *support scheme harmonization or compatibilization* in Europe, whether with a North Seas focus or not, e.g. Busch et al. [43], EEG [3], or Nieuwenhout and van Hout [9]. It is a core issue for a

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governance framework for the NSOG, bears many relations to other regulatory questions and is often addressed in the reviewed studies, albeit with different levels of detail.

Regarding *operation and congestion management*, NSCOGI [44,45] provides an introductory review of the questions concerning an offshore renewable generator connected to an interconnector. Finally, one of the objectives of the European Commission for projects of common interest is streamlined *permitting procedures* (also the focus of an NSCOGI working group). As indicated, permitting can be an important factor to transmission projects delays, and European harmonization should be studied and coordinated.

Thus, generation and transmission in the North Seas have technical, economic and social characteristics which result in uncertainties and governance challenges. These characteristics qualify the NSOG as a complex socio-technical system, and give the multiple studies their relevance, but also create comparability challenges. It is uncertain which typology the grid will follow, and which one provides the highest net benefits, who are the winners and losers and what are the barriers to implementation. Nonetheless, actors continue to invest in and regulate the power system, locking-in development of the NSOG to certain pathways, without a comprehensive analysis of the possibilities.

### 2.2. Categorization Framework

This section details the review categorization framework and relates it to the NSOG characteristics. Connolly et al. [46], Foley et al. [47], Bazmi and Zahedi [48], and Pfenninger et al. [11] provide reviews of energy models. However, De Decker and Woyte [6] is the only peer-reviewed one dedicated to the NSOG, reviewing the main drivers, policy and industry initiatives, and concept proposals up to 2009. Furthermore, it indicates that most studies it considers are preliminary concepts, with only two published studies performing a cost and benefit analysis of the NSOG. Among non-peer reviewed reports, ENTSO-E [49] compares their results to those of NSCOGI [50], while Egerer et al. [51], Haileselassie and Uhlen [52], Pinto [53] and Cole et al. [32] mention or briefly review some existing offshore grid studies. Therefore, a recent and comprehensive review of the modelling studies of the NSOG does not exist, despite the number of studies and the grid being a priority for European climate and energy goals.

The categories were selected based on the authors’ own judgment, after considering the energy models reviews mentioned and best practices for the development of wind integration studies from Holttinen [54]. The first category, the *main research question*, indicates the focus of the study, which influences the choice of methodology, data and assumptions. Its analysis should provide information on gaps of research on the grid. As a complex socio-technical system, the NSOG provides a number of technical, economic and social issues to focus on. The *target group* of the studies is closely related to the research question, albeit possibly being less important to the review.

Although it could be more refined (e.g. discriminating between day-ahead, intraday and balancing timeframes) the separation of the *research horizon* between the investment and operation is adequate for this review. Logically, certain research questions require a specific horizon (studying long-term impacts of support schemes calls for an investment approach), but comprehensive projects can use both horizons, albeit in separate sub-studies.

If all reviewed studies use bottom-up modelling, the *model method* (optimization, equilibrium or simulation) further refines the methodology classification. The model method should be defined according to the research questions since the results types vary according to the chosen method. Model methods arrive at results by different assumptions on system entities (be they actors, technical components or institutions) and interaction (e.g. existence of an objective function, rules of behavior).

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The *criteria* is closely related to the research question, and are of two types: criteria for the model method (i.e. criteria used for solving the model algorithm), and result analysis criteria. Typically, all model method criteria are part of the analysis criteria. Nonetheless, as a rule analysis criteria are more numerous, and this review considers the latter group. Importantly, result presentation should be reviewed not only regarding the sufficiency of criteria analyzed, but also the resolution and quality of the analysis.

Since the NSOG is characterized as geography-dependent and bottom-up modelling studies represent generation, transmission and load, the *grid resolution* is relevant. Models can range from using one grid node per country to accurate representations of power systems with thousands of nodes and components. A further constraint on result resolution is the *actor resolution*, where a distinction must be made between resolution of the methodology and of presentation of results. As is indicated below, study methodologies may have a resolution up to a national or actor (i.e. consumers, producers and TSOs) level, but present results only at an European or a national level. In this review actor resolution refers to the results presentation, since this is the relevant parameter for external readers.

The *final horizon year* and *geographic coverage* are practical choices crucial to answering research questions, considering the path- and geography-dependency of the NSOG. However, feasibility and data availability considerations also influence these choices.

Finally, studies will vary in the *number of scenarios, typologies and sensitivity analyses*, with any combination being possible. Scenarios refer to exogenous assumptions for the models, such as fuel and $CO_2$ prices or onshore conventional generation, while different typologies apply to the same scenario. As for sensitivity analyses, these are defined as limited changes to scenarios and typologies (e.g. fuel and $CO_2$ prices, technology costs and level of OWP development).

Therefore, the categorization framework analyses characteristics often related to the research questions and the model method used. Thereby it focuses on important issues of the studies: the modelling and results, and their differences. Coupled with the system characterization and indicators, they provide a stable reference for this review.

**Table 1:** North Seas offshore grid bottom-up modelling studies.

| Project | Authors and Reference | Publication Year | 1st Research Question | 2nd Research Question | Target Group | Model | 1st Criteria | 2nd Criteria | 3rd Criteria | Research Horizon | Grid Resolution per Country | Actor Resolution | Final Horizon Year | Scenarios | Typologies | Sensitivity Analyses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Huertas-Hernando et al. [55] | 2010 | Investment & Planning | Operation & Reliability | Scientific Community | Optimization | NSB with CO2 | Investment Costs/Benefits[a] | | Investment | Multiple | National | 2030 | 1 | 2 | 0 |
| OffshoreGrid | De Decker and Kreutzkamp [8] | 2011 | Investment & Planning | | Policy Makers | Optimization | NSB with CO2 | | | Investment | Few nodes | National | 2030 | 1 | 4 | 0 |
| | Trötscher and Korpås [56] | 2011 | Investment & Planning | Operation & Reliability | Scientific Community | Optimization | NSB with $CO_2$ | | | Operation | Few nodes | National | N/A | 1 | 2 | 3 |
| | Tröster et al. [57] | 2011 | Investment & Planning | | Policy Makers | Optimization | NSB with $CO_2$ | RES Int./Curtailment[a] | | Investment | Multiple | National | 2050 | 1 | 1 | 0 |
| NSCOGI | NSCOGI [50] | 2012 | Investment & Planning | Operation & Reliability | Policy Makers | Optimization | NSB with $CO_2$ | | | Investment | Few nodes | National | 2030 | 1 | 2 | 1 |
| TYNDP 2012 | ENTSO-E [58] | 2012 | Operation & Reliability | Investment & Planning | Policy Makers | Optimization | NSB with $CO_2$ | Avoided Emissions | RES Int./Curtailment[a] | Investment | Multiple | National | 2020 | 2 | 1 | 1 |
| | Egerer et al. [35,51] | 2012 | Energy Policy | Operation & Reliability | Scientific Community | Optimization | NSB with $CO_2$ | Congestion Revenues | | Operation | Multiple | Prod./Cons./Cong. | 2020 | 2 | 3 | 0 |
| NSTG | Ciupuliga et al. [59] | 2012 | Operation & Reliability | | Scientific Community | Optimization | NSB with CO2 | RES Int./Curtailment | Avoided Emissions[a] | Operation | One node | National | 2030 | 1 | 1 | 11 |
| NSTG WP6 | Ciupuliga [60] | 2013 | Operation & Reliability | | Scientific Community | Optimization | NSB with $CO_2$ | Reliability | RES Int./Curtailment[a] | Operation | One node | Regional | 2030 | 1 | 3 | 1 |
| NSTG WP7 | Nieuwenhout and van Hout [9] | 2013 | Investment & Planning | Energy Policy | Policy Makers | Optimization | NSB with $CO_2$ | | | Investment | One node | Prod./Cons./Cong. | 2030 | 1 | 3 | 1 |
| NSTG WP5 | Rodrigues et al. [61] | 2013 | Technology | Operation & Reliability | Scientific Community | Optimization | NSB without $CO_2$ | Power losses | Reliability | Operation | One node | Prod./Cons./Cong. | N/A | 1 | 1 | 3 |
| | Haileselassie and Uhlen [52] | 2013 | Operation & Reliability | | Scientific Community | Optimization | Reliability | | | Operation | One node | National | N/A | 1 | 1 | 4 |
| | Drees et al. [62] | 2013 | Investment & Planning | Operation & Reliability | Scientific Community | Optimization | NSB with $CO_2$ | Investment Costs/Benefits | | Investment | Multiple | National | 2060 | 1 | 4 | 0 |
| | Strbac et al. [10,63] | 2014 | Investment & Planning | Energy Policy | Policy Makers | Optimization | NSB with $CO_2$ | | | Investment | Few nodes | National | 2040 | 4 | 5 | 3 |
| | Cole et al. [32,64] | 2014 | Energy Policy | Investment & Planning | Policy Makers | Optimization | NSB with $CO_2$ | RES Int./Curtailment | Investment Costs/Benefits[a] | Investment | Few nodes | National | 2030 | 3 | 2 | 2 |
| TYNDP 2014 | ENTSO-E [49] | 2014 | Investment & Planning | Operation & Reliability | Policy Makers | Optimization | NSB with $CO_2$ | Avoided Emissions | RES Int./Curtailment[a] | Investment | Few nodes | National | 2030 | 4 | 1 | 0 |
| | Busch et al. [43] | 2014 | Energy Policy | | Policy Makers | Equilibrium | NSB with $CO_2$ | Avoided Emissions | Avoided Fuel Imports[a] | Operation | N/A | National | 2020 | 1 | 1 | 1 |
| | Buatois et al. [65] | 2014 | Operation & Reliability | | Scientific Community | Optimization | Reliability | | | Operation | Few nodes | National | 2030 | 3 | 1 | 0 |
| SAS | Torbaghan et al. [66] | 2014 | Energy Policy | Investment & Planning | Policy Makers | Optimization | NSB without $CO_2$ | | | Investment | One node | Prod./Cons./Cong. | 2025 | 1 | 1 | 3 |
| SAS | Azari et al. [67] | 2014 | Investment & Planning | Energy Policy | Scientific Community | Optimization | NSB with $CO_2$ | Investment Costs/Benefits | | Operation | One node | National | N/A | 3 | 2 | 0 |
| | Jaehnert et al. [68] | 2014 | Investment & Planning | Operation & Reliability | Policy Makers | Optimization | NSB with $CO_2$ | Investment Costs/Benefits | | Investment | Few nodes | National | 2030 | 1 | 1 | 1 |
| NSTG | van der Meer et al. [69] | 2015 | Operation & Reliability | | Scientific Community | Optimization | Reliability | | | Operation | Multiple | National | 2025 | 1 | 2 | 2 |
| | Torbaghan et al [70] | 2015 | Investment & Planning | Energy Policy | Scientific Community | Optimization | NSB with $CO_2$ | Investment Costs/Benefits | | Investment | Few nodes | National | 2025 | 1 | 5 | 0 |
| | Torbaghan et al. [71] | 2015 | Energy Policy | Investment & Planning | Policy Makers | Optimization | NSB with $CO_2$ | Investment Costs/Benefits | | Investment | One node | National | N/A | 1 | 1 | 2 |
| | Chowdhury and Yanushkevich [72] | 2015 | Operation & Reliability | | Scientific Community | Optimization | Reliability | | | Operation | Few nodes | National | 2030 | 3 | 1 | 0 |
| | Chondrogiannis and Blanco [73] | 2015 | Operation & Reliability | Energy Policy | Scientific Community | Optimization | Imbalance settlement | | | Operation | One node | National | N/A | 1 | 1 | 7 |

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[a] The study includes additional criteria to the main ones indicated

## 3. Results and Discussion

### 3.1. Categorization Framework Analysis

Table 1 presents the reviewed studies and their classification according to the categorization framework. This section analyzes the reviewed studies in four parts, namely in relation to the main categories, to relevant indicators, to the offshore grid characteristics and to remaining aspects. However, for brevity, when categories are related to the NSOG characteristics they are analyzed only in the characteristics sub-section. Figure 4 presents the distribution of the studies according to some categories of Table 1. Although the categories analysis is presented below, already an uneven distribution in the actor resolution and model categories stands out from the data visualization.

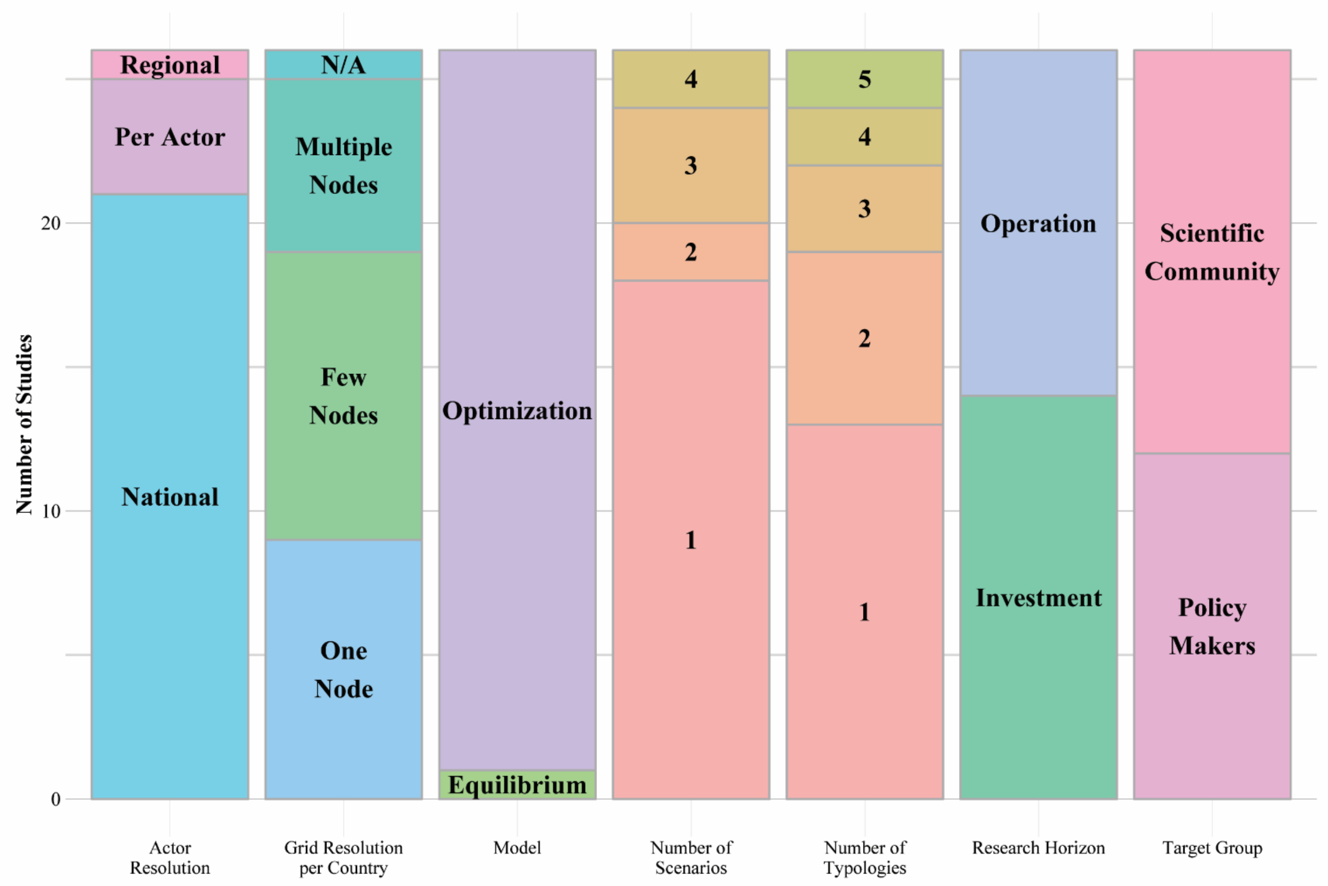

**Figure 4: Studies distribution according to categories.**

The *main research questions* of the reviewed studies are investment & planning and operation & reliability, while an energy policy or technological focus is less frequent. Since this review considers offshore grids specific to the North Seas this may influence the absence of technological focus, since multiterminal HVDC transmission technology studies can use abstract grids. Additionally, development of HVDC breakers, DC-DC converters and standardization are challenging partly due to non-technical issues such as feedback between private research investment and sufficient demand. Therefore, studies of these aspects may use methodologies other than bottom-up modelling.

On the other hand the secondary role of energy policy as a research question is not an artifact from the delimited scope of this review, or from stakeholders perceiving the issue as marginal. Quite the contrary, as indicated by analyses such as from Flynn [40] and Woolley [38]. European and national organizations will directly affect the pathway of the NSOG through regulation, financing and planning of power markets in the North Seas. What more, policy makers are a relevant target group for the studies, many of which are developed by or commissioned by governmental organizations. Also, energy policy challenges are frequently dealt with qualitatively by the reviewed studies. Interestingly, Pfenninger et al. [11] find energy models can be overly complex, and thus unsuitable for policy analysis, or disregard socio-political factors. In summary, energy policy is extensively dealt with by the studies, but rarely by their models, with the recent exception of Torbaghan et al. [71]. The difficulty of endogenous representation of energy policy may contribute to this fact.

For any study, the research question should influence the *methodology choice*, as is the case for the reviewed studies. Almost all models are optimization ones, with the maximization of net social benefits or minimization of costs, usually considering $CO_2$ emissions costs. Hence, no study uses a simulation model, even though Pfenninger et al. [11] indicate simulation models can contribute to understanding complex systems (of which the NSOG is one). Thus, the underrepresentation of energy policy as a research question can lead to the absence of simulation models.

*Actor resolution* is a gap in the presentation of study results, with less than a fifth detailing net welfare by producers, consumers and congestion rent. Thus, future research should strive to always present results detailed per countries and actors. Even more so since studies that did found that welfare is unequally distributed at both levels, and indicate this as a significant barrier to the development of an integrated grid.

The majority of studies looks to the NSOG at most up to 2030, the year of the current Climate and Energy Policy Framework and ENTSO-E’s 2014 TYNDP. The *horizon year choice* depends on its relevance to the research question, data availability and capacity of the methodology to remain adequate for the period under analysis. Regarding the first factor, a more integrated NSOG will only be possible closer to 2030, or even later. Thus 2020 can be currently considered too restrictive, while NSOG studies for 2040 or later are interesting, especially considering the 2050 European goals. However, data availability can be a barrier to developing scenarios beyond 2030, and even 2030 itself could have posed difficulties for the earlier studies reviewed. Finally, NSOG models beyond 2030 face increasing uncertainty not only on data, but also on pathways, due to factors such as future technology developments (e.g. storage and technology costs). Thus, 2030 is a compromise between answering research questions and modelling limitations, while the same can be stated for 2020 regarding earlier studies.

### 3.2. Indicator Analysis

The indicators analyzed are offshore wind capacity by scenario, cabling length vs. offshore wind capacity, net social benefits per scenario and scenario $CO_2$ and generation costs. Due to the varied availability, each indicator includes only those scenarios or studies for which data was available. Furthermore, although other indicators are interesting (e.g. investment costs), there is not data from enough studies to warrant their elaboration.

For the reviewed studies with available data, Figure 5 presents the *offshore wind power installed capacities*, which can be exogenous (obtained through scenarios) or endogenous (obtained through the model solution). Exogenous methods for scenario capacities include compiling existing wind farm projects, assessing the wind resource potential and using 3rd party scenarios. On the other hand, endogenous methods usually optimize offshore wind investments, from either a social or private perspective, or use project revenues and costs or economic cost-resource curves. The use of equilibrium or simulation to endogenously model offshore wind capacity investments is scarce, as indicated. Given the number of methods to determine offshore wind capacities and possible intra-method variations, it is not surprising differences are significant for all available horizons. Consequently, for 2030 (the most frequent horizon year) OWP capacities range from 30 to 150 GW, with an average of 86 GW. As a comparison, EWEA [74] in its scenarios considers a total capacity from 19.5 to 27.7 GW in 2020.

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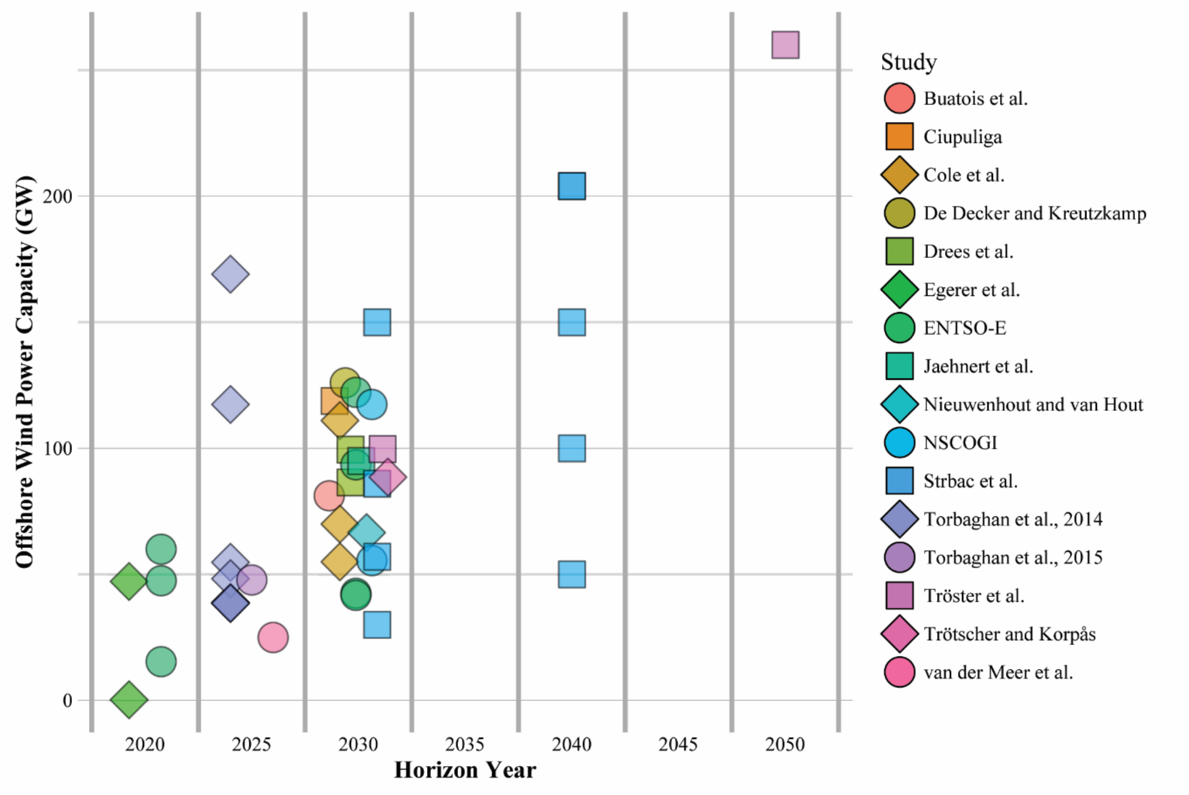

**Figure 5: Offshore wind power installed capacities.**

Figure 6 presents the *cabling lengths and OWP capacities* of scenarios and typologies (considering only subsea DC cables when such differentiation is made). Length increases with installed capacity, and two pattern groups can be identified. The first has a ratio under 200 km/GW and generally comprises more integrated typologies, while the second is above 200 km/GW and comprises radial typologies. However, there are exceptions such as De Decker and Kreutzkamp [8] and ENTSO-E [58].

Analyzing intra-study variations, combinations of scenarios and typologies can affect cabling length or installed capacity, separately or in combination. Thus, the OffshoreGrid cabling length increases for constant capacity, while the 2014 TYNDP has constant length for different capacities. Furthermore, no relation between typology category (radial, hub or meshed) and cabling length across the studies can be identified, though assumptions and data publication affects this. In this way, a given typology does not automatically result in more or less cables, nor in higher or lesser environmental impacts from cable lying, a benefit of a meshed NSOG mentioned in studies. For example, all meshed typologies from Cole et al. [32] have less cables for the same OWP capacity, but the inverse is true for De Decker and Kreutzkamp [8].

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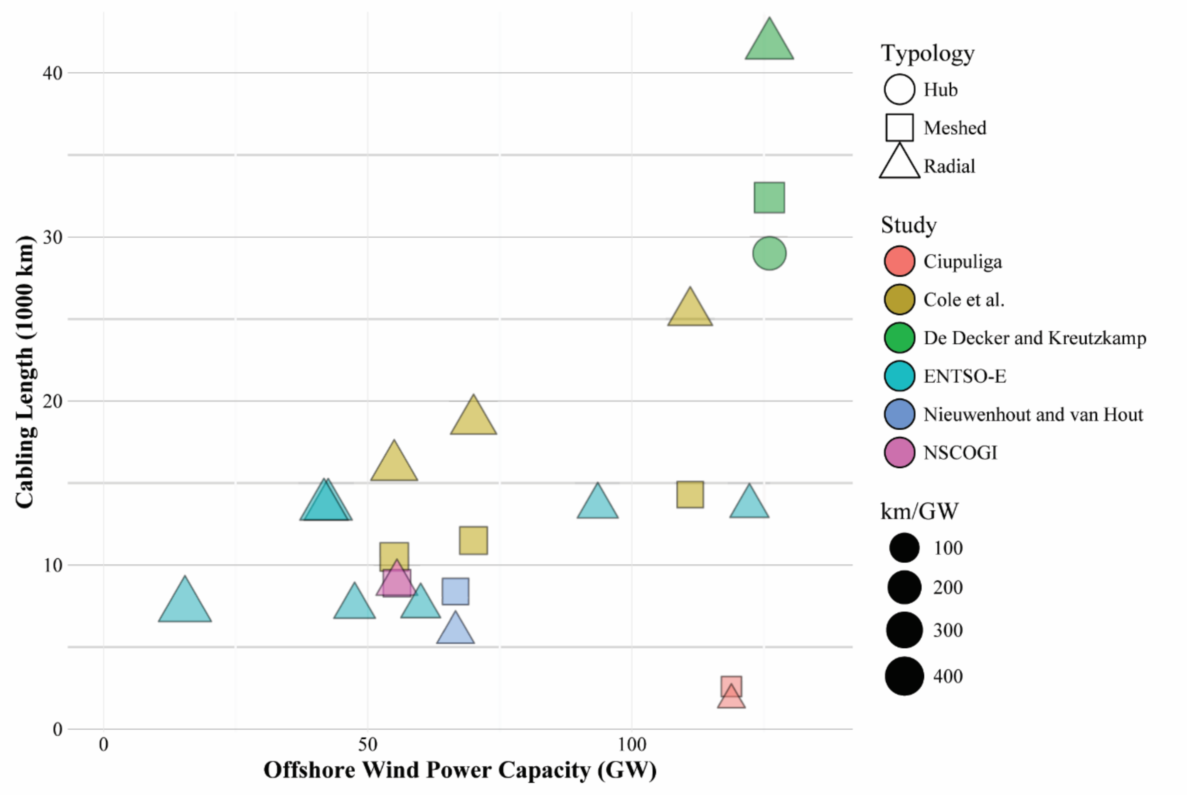

**Figure 6: Cabling lengths and offshore wind power capacities.**

Figure 7 presents available *net social benefits (NSB)* of the reviewed studies. These must be compared with caution since they can be absolute or relative to a reference case, and consider different costs and benefits. Moreover, of the reviewed studies only seven present NSB data, a small share. Nonetheless, net social benefits increase with the horizon year (to which the increase in wind capacity contributes) and more integrated typologies. For 2030, NSB range from B€1.33 to 21.00, while for 2025 the range is from B€-15.38 to 8.45 (where negative values result from including capacity support expenditures).

The higher benefits of an integrated grid is a main argument for the coordination of its development and the sharing of interconnection and connection. Besides the studies that provide a total NSB value, a few others provide an annualized value. Both types indicate that an integrated grid is more beneficial than a less integrated one, at an European level. The exception is Torbaghan et al. [66], but if it considered capacity support expenditures in the objective function the model would arrive at different capacities, and possibly higher net social benefits.

The higher NSB of integrated typologies must be qualified by two considerations. Firstly, these benefits must be weighed against more challenging governance, operation, compatibilization of regulation and technological uncertainty. Thus, gains may be too small to incentivize actors in integrating the NSOG. Secondly, national and actor net benefits are unevenly distributed, with winners and losers at both levels. Thus, without an adequate costs and benefits allocation mechanism countries and actors may have incentives to actively resist an integrated offshore grid.

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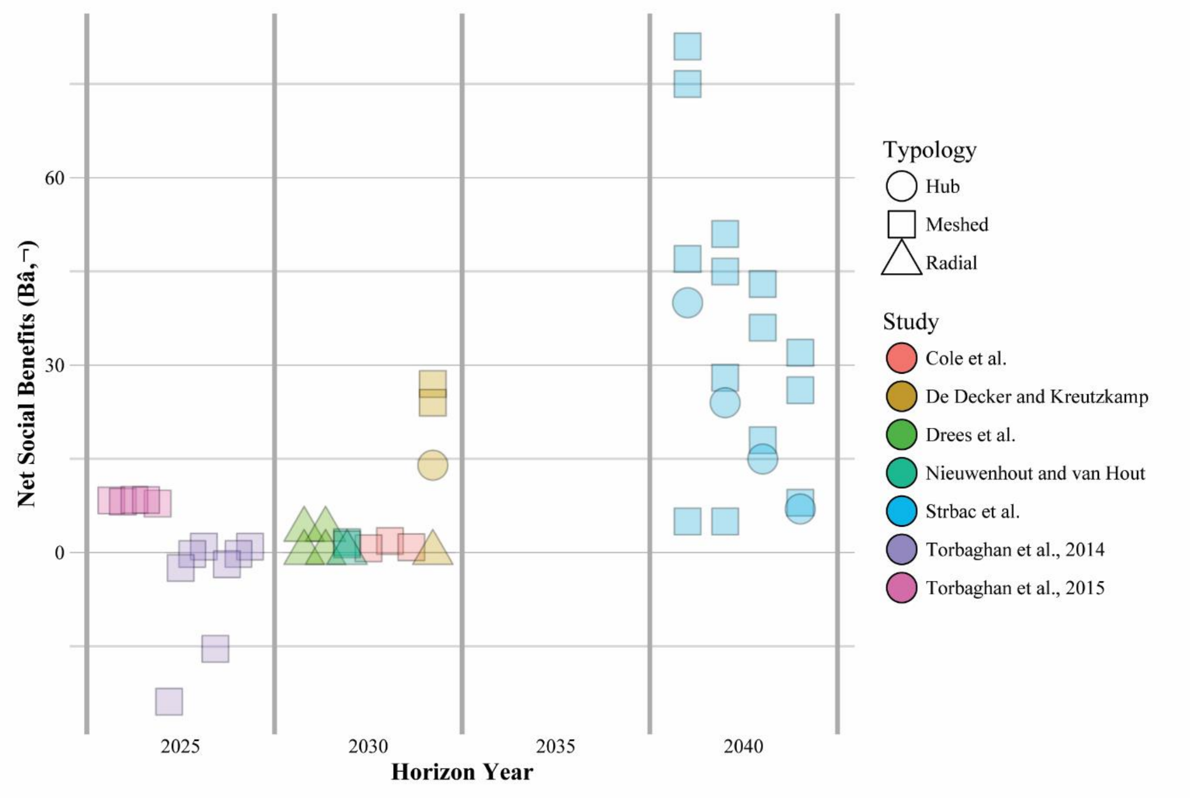

**Figure 7: Net social benefits of offshore grid studies.**

Figure 8 presents the available *$CO_2$ prices and fuel and electricity generation costs*, also indicated in Table 2. Studies do not always indicate if they refer to primary fuel costs or electricity generation costs, and if the latter considers $CO_2$ prices and operation & maintenance costs. Hence, this data must be considered with caution.

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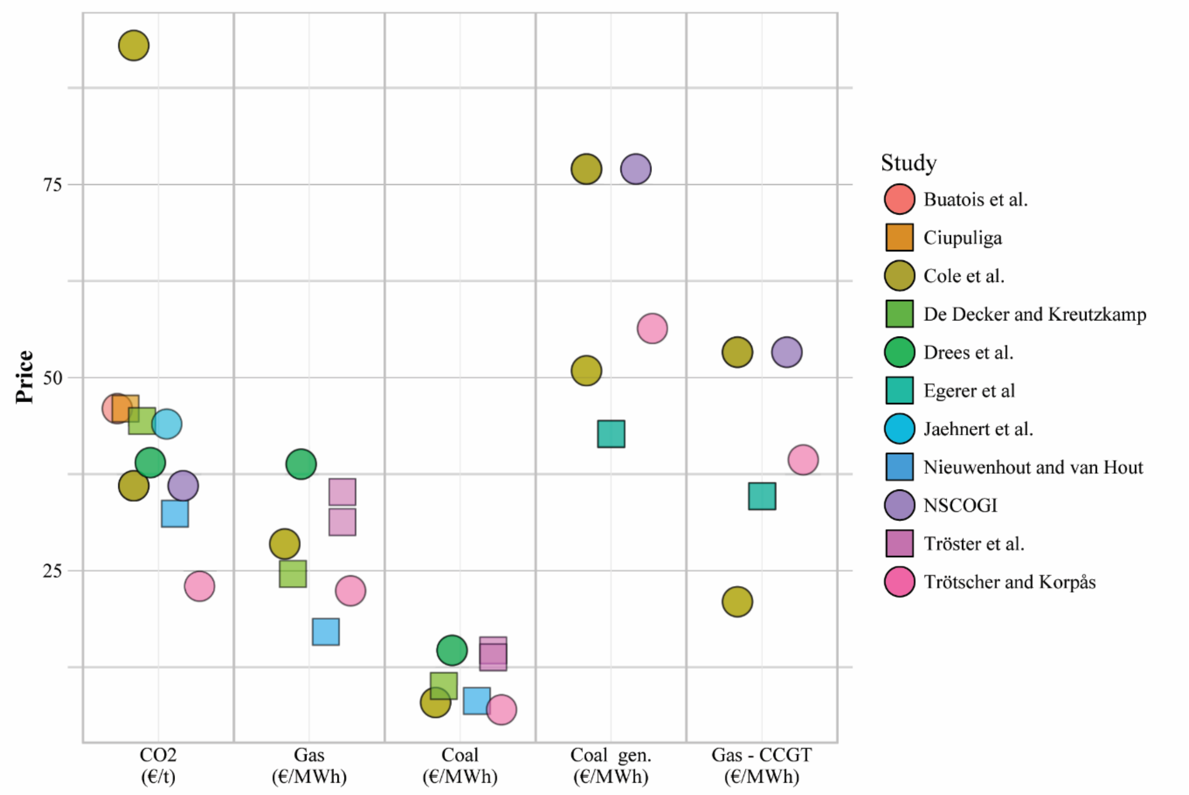

**Figure 8: CO2 and fuel prices, and electricity generation costs.**

Generation costs directly impacts dispatch order, generation technology mix, electricity prices and $CO_2$ emissions, and thus affect generation investment. For example, in its fuel costs sensitivity analysis Cole et al. [32] indicate that "when considering higher fuel prices, the benefits are increased in the same proportion", for both the radial and meshed typology. Studies should therefore treat factors affecting generation (and transmission) costs with adequate data presentation and consideration of different scenarios or sensitivity analyses.

Available $CO_2$ and fuel prices and net benefits indicate no consistent pattern between higher prices and higher net benefits. For instance, Drees et al. [62], NSCOGI [50] and Cole et al. [32] have the highest fuel prices, but not the highest net benefits – even considering only operational net benefits, those of Strbac et al. [10] are much higher.

Other factors that influence results include forecasted demand, intertemporal modelling of inflexibility and storage, load flow model and resolution, and consideration of power losses. Furthermore, relative generation costs between technologies also affect the dispatch order, the generation mix and resultant emissions. In summary, while higher scenario price levels may lead to higher absolute benefits for an individual study, interstudy comparison indicates no such relation. This is due to the influence of relative price levels and other factors.

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**Table 2:** CO$_2$ and fuel prices, and electricity generation costs.

| Authors | Scenario | Horizon Year | CO$_2$ | Primary Fuel (€/MWh) | | Electricity (€/MWh) | |
|---|---|---|---|---|---|---|---|
| | | | (€/t) | Gas | Hard Coal | Coal | Gas CCGT |
| Buatois et al. | Single | 2030 | 46.0 | | | | |
| Ciupuliga | Reference | 2030 | 46.0 | | | | |
| Cole et al. | Scenario 1 | 2030 | 93.0 | 28.5 | 8.0 | 50.9[b] | 21.0[b] |
| Cole et al. | Scenario 2 | 2030 | 36.0 | | | 77.0 | 53.3 |
| Cole et al. | Scenario 3 | 2030 | 36.0 | | | 77.0 | 53.3 |
| Cole et al. | Fuel Sensitivity | 2030 | 93.0 | | | 77.0 | 53.3 |
| Cole et al. | CO2 Sensitivity | 2030 | 36.0 | 28.5 | 8.0 | 50.9 [b] | 21.0 [b] |
| De Decker and Kreutzkamp | Single | 2030 | 44.4 | 24.6 | 10.1 | | |
| Drees et al. | EWI A | 2030 | 39.0 | 38.8 | 14.7 | | |
| Drees et al. | EWI B | 2030 | 39.0 | 38.8 | 14.7 | | |
| Egerer et al. | 2009 | 2020 | | | | 42.7 | 34.7 |
| Egerer et al. | Wind+ | 2020 | | | | 42.7 | 34.7 |
| Jaehnert et al. | Single | 2030 | 44.0 | | | | |
| Nieuwenhout and van Hout | Reference | 2030 | 32.4 | 17.1 | 8.2 | | |
| NSCOGI | RES+ | 2030 | 36.0 | | | 77.0 | 53.3 |
| NSCOGI | Reference | 2030 | 36.0 | | | 77.0 | 53.3 |
| Tröster et al. | Scenario A | 2050 | | 35.2 | 14.7 | | |
| Tröster et al. | Scenario A 2030 | 2030 | | 31.3 | 13.8 | | |
| Trötscher and Korpås | TradeWind | 2030 | 23.0 | 22.4 | 7.0 | 56.4 | 39.4 |

### 3.3. NSOG Characteristics Analysis

Since the essential strength of bottom-up models is the ability to simulate system details, analysis must also relate the studies to the characteristics presented in section 2. Regarding *generation expansion coordination*, approaches vary from the use of scenarios for all generation expansion (including offshore wind), to endogenous capacity expansion for all generation technologies or wind only. This is one of the main factors for the large differences in offshore wind capacity of Figure 5. Generation expansion is coupled with transmission expansion in the studies also through a number of methods, generally through simultaneous or iterative endogenous optimization. Another option is using endogenous and exogenous (scenario) expansion for different time periods. For example, transmission projects of the 2014 TYNDP may be considered exogenously, with endogenous transmission expansion from 2020 onwards.

The plausibility of *simulated typologies* may not be a relevant question for studies focusing operation or technical feasibility, but is so for studies focusing energy policy or investment & planning. In this case, more probable typologies may be obtained by considering existing transmission and generation projects, but the use of scenarios and sensitivity analysis is once again warranted. Furthermore, simulation models could address the complexity of the NSOG, and thus result in more realistic typologies.

*Uncertainty in load and generation* is addressed through the use of historic or synthetic correlated time series, especially for OWP generation. As for *hydropower generation and storage*, there are three main approaches. These are ignoring intertemporal constraints, or using a two-tiered model (with the model with lower temporal resolution determining the water value) or an artificial lower maximum generation capacity. Modelling of these constraints can be warranted due to the importance of Scandinavian storage capacity. Moreover, the distributional effects of storage are not straightforward, as shown by the results of Midttun et al. [75]. Thus, statements such as “increased interconnection capacity always benefits consumers of importer countries” usually do not apply directly.

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[b] Does not include the CO$_2$ costs

*Strategic behavior* of market participants is not considered in most studies, who assume perfect competition with marginal cost bidding of supply. Interestingly, the model used by Busch et al. [43] allows strategic behavior, and the study finds two thirds of the benefits can be obtained by support scheme redesign to reduce "over-support". Thus, while strategic behavior is most often not addressed, it may be an important factor.

$CO_2$ emissions are the only externality considered consistently in net social benefits. Other *externalities* such as environmental impact of cabling and landfall installations and effects on existing merchant interconnectors are presented separately, and usually not valuated. More integrated typologies do not lead automatically to lower negative externalities, and therefore indicators on those externalities such as cabling length and number of landfalls should be provided. Moreover, increased interconnection capacity may lead to full price convergence, directly impacting merchant interconnectors.

The *lumpiness and long operational life* of assets are treated only by studies taking the investment perspective, through cost-benefit analyses over a period of 30 to 40 years and the establishment of minimum expansion capacities. On the other hand, *asset specificity* is addressed in case studies on stranded investments or through qualitative analysis. Finally, Ciupuliga [60] found *loop flows* to be a significant issue, and recommends the use of accurate load flow models besides market models. Moreover, while economies of scale in transmission expansion are usually not modelled, this is justifiable due to the fragmentation of the NSOG actors. These characteristics impose therefore their own specific requirements on modelers, who need to justify their choices accordingly.

The main NSOG *technological issues* are costs and VSC multiterminal grids development considering control strategies, standardization and large circuit breakers. Most studies usually assume fixed transmission investment costs proportional to line capacity and length (with a possible fixed cost per capacity). On the other hand, offshore wind farm investment costs may change, as in Tröster et al. [57]. Nieuwenhout and van Hout [9] do realize a survey of offshore transmission costs, and Trötscher and Korpås [56] use different HVDC breaker typologies and cost parameters, which determined the HVDC multiterminal grid as economically viable. As for *technological development*, studies focusing on operation and reliability may consider different VSC-HVDC control strategies, such as Haileselassie and Uhlen [52] or Rodrigues et al. [61]. Nonetheless, consideration of HVDC circuit breaker uncertainties such as cost is rare in the models reviewed, but these are extensively treated in literature outside of the scope of this review.

Offshore grid typologies are exhaustively treated with optimization models in all horizons and for the main research questions, as Table 1 indicates. Nonetheless, indicator comparison between studies demonstrates the difficulty of generalizing the advantages of more or less *integrated typologies*. Additionally, while the N-1 contingency rule is frequently used in studies, further research is needed on other *reliability* aspects and impacts on the onshore grid which studies indicate as being important, e.g. Ciupuliga [60] and Tröster et al. [57].

Approaches to treat the *geography dependency* include portfolio analysis to determine wind farms suitable to hub connection, e.g. De Decker and Kreutzkamp [8], detailed heuristics for the optimum connection typology for identified wind farms, e.g. Cole et al. [32], and complementary abstract cases studies. However, the use of 3rd parties studies and aggregation of OWP capacities at a national level with low resolution grids is as frequent. Thus, future studies must consider carefully the choice of the grid typology, and the use of available typologies must be justified.

Concerning the *timing dependency*, static (one-period) modelling is more frequent, to which the size of dynamic optimization models may be a factor. Hence, even though bottom-up models are more adequate to represent technological characteristics, a compromise in the level of details is frequent and justified given the research questions. Nonetheless, the scarcity of dynamic models is a gap in NSOG research which prevents modelling timing dependency. Pfenninger et al. [11]

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indicate simulation models can contribute to this temporal and spatial resolution challenge, but as indicated studies reviewed comprise practically only optimization models.

Regarding *endogenous modelling of regulation*, Torbaghan et al. [66,71] do model capacity and energy support schemes for offshore wind, and Busch et al. [43] analyze different cost allocation schemes. However, there is a need for further endogenous modelling of regulation in bottom-up studies of the NSOG. This results from the range of regulatory tools available, the importance of energy policy in Europe and of policy makers as a target group.

### 3.4. Other Considerations

One may question the *usefulness of bottom-up studies* in providing advice to policy makers, given the broad range of assumptions, methodologies and results. However, cost-benefit analysis of the grid is an improvement on the remark of von Hirschhausen [28] on supergrids, that "that few studies surveyed include an economic analysis beyond some rough financial indicators, such as costs". Additionally, even negative or small net benefits for integrated solutions highlight points of attention for policy design: distribution of benefits and costs between countries and actors, technology costs, support mechanisms, and expansion planning coordination. The more frequent use of least-regret approaches can also contribute to policy on the grid, since it helps to indicate whether anticipatory investments are beneficial [10]. Finally, when studies conduct sensitivity analyses these are punctual, varying one parameter at a time, and the computational requirements of offshore grid models limits the feasibility of more comprehensive methods. Nonetheless, the application of a method such as the elementary effects indicated by Saltelli and Annoni [76] can provide interesting results and be feasible for NSOG models.

Another point is the importance of considering *marine spaces other than the North Sea*. Studies demonstrate the grid impacts not only power markets on the North Sea shore but also their neighbors, and that wind capacities in other Northern seas can be up to 40% of total capacity [5,8]. Therefore the inclusion of all northern seas is an important consideration.

*Future technical developments* that can impact the NSOG comprise non-hydro storage and demand side management. However, studies addressing these questions are few and with many simplifying assumptions, preventing more general conclusions, except that they may increase net social benefits [10,67]. There is ample space for future research to study these under broader assumptions and different modelling approaches.

Finally, regarding the *result publication quality*, studies can improve the access to data and assumptions used (a frequent finding in energy modelling literature reviews), and should avoid simultaneously citing multiple sources for multiple data.

## 4. Conclusions

Restructured electricity markets, transmission systems and the offshore grid can be seen as systems of increasingly constrained boundaries, which share common characteristics but also add further ones. The offshore grid has singular technical, economic and social characteristics, and as a consequence different research questions entail the use of different methodologies. Therefore, this study reviewed the bottom-up energy models considering that a single, perfect representation of the offshore grid does not exist, but that relevant insights can be gathered and future research areas can be identified nonetheless.

The review shows that bottom-up modelling focuses on the investment & planning and operation & reliability research questions, using optimization models to address them. Net social benefits at a regional level generally increase with higher offshore wind installed capacities and more integrated grids, but studies present large differences in assumptions, methodology and publication of results. The variation in installed capacities is the main illustration of these differences. Its analysis does not allow to identify more clear patterns relating offshore wind, grid integration, cable length and investment and operation costs. Additionally, there is a high potential for research on future technical developments such as non-hydro storage and demand side management.

Nonetheless, the grid can provide net benefits from more efficient dispatch, greater connection of wind power, increased system flexibility and reliability, and interconnection of power markets and Nordic storage. Also, a meshed typology may increase those benefits in comparison to a radial one, requiring less investments and reducing offshore wind curtailment, with other possible non-monetary benefits. The latter include increased resilience for individual projects, reduced environmental impacts of cable laying and onshore infrastructure, increased competition, and technological and industrial development.

On the other hand, a meshed grid without adequate allocation of costs and benefits creates losers as well as winners among North Seas countries and their neighbors. Benefits and costs distribution also affects producers, consumers and transmission operators, with multiple factors determining the final effects, which are not straightforward. The offshore grid also involves so far unproven technology (especially control strategies and large HVDC breakers), and an integrated grid could require greater investments than a radial one. Moreover, the onshore and offshore power systems need to be jointly considered for security of supply, although this also applies to a radial typology. There are thus significant technical, governance and regulatory challenges for a meshed grid, which in some studies present only marginally greater benefits than a radial solution. Moreover, frequently the governance and regulatory challenges are dealt only qualitatively.

Thus, not surprisingly studies indicate the offshore grid will develop gradually. National shared transmission and bilateral interconnector projects can be followed by international pilot projects, which only then would give way to more complex ones. However, there is not a consensus if this would happen in a formal framework, and even if that framework is needed. From a governance standpoint, the studies reviewed do not present a clear case for immediate and full cooperation between European actors, although they do contribute to energy policy.

This and other reviews of energy systems models indicate simulation and equilibrium models can address some limitations of optimization models applied to the grid. However, irrespectively of the model used, future research should consider the recommendations of this review to represent the relevant system components. Interesting attributes include but are not limited to endogenous regulation, endogenous transmission and generation expansion, strategic behavior and actor agency. Thus, a promising approach is a simulation model with endogenous regulation that is able to support policy on the North Seas offshore grid, considering the technical developments and actor strategies. Complementarily, all studies should

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aim for high quality presentation and resolution of data, assumptions and results, independently of the research question and methodology.

Besides these results, the simple and effective methodology developed can be applied to other energy systems model reviews. It considers the studies of interest, the system characteristics, a categorization framework and relevant indicators. Although these will vary according to the system, whenever there is an adequate number of studies this provides a more structured approach to make sense of abundant information.

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## References

[1] EC European Commission. A policy framework for climate and energy in the period from 2020 to 2030. 2014.
[2] IEA International Energy Agency. Energy Policies of IEA Countries - The European Union. 2014.
[3] EEG Energy Economics Group - Vienna University of Technology, Institute of Energy Systems and Electrical Drives. Final report of the beyond2020 project - approaches for a harmonization of RES(-E) support in Europe. 2014.
[4] Rodrigues S, Restrepo C, Kontos E, Teixeira Pinto R, Bauer P. Trends of offshore wind projects. Renew Sustain Energy Rev 2015;49:1114–35. doi:10.1016/j.rser.2015.04.092.
[5] EWEA European Wind Energy Association. The European offshore wind industry - key trends and statistics 2014. 2015.
[6] De Decker J, Woyte A. Review of the various proposals for the European offshore grid. Sel Pap World Renew Energy Congr - XI 2013;49:58–62. doi:10.1016/j.renene.2012.01.066.
[7] Spro OC, Torres-Olguin RE, Korpås M. North Sea offshore network and energy storage for large scale integration of renewables. Sustain Energy Technol Assess 2015. doi:10.1016/j.seta.2014.12.001.
[8] De Decker J, Kreutzkamp P. Offshore Electricity Grid Infrastructure in Europe. OffshoreGrid; 2011.
[9] Nieuwenhout FDJ, van Hout M. Cost, benefits, regulations and policy aspects of a North Sea Transnational Grid. ECN; 2013.
[10] Strbac G, Moreno R, Konstantelos I, Pudjianto D, Aunedi M. Strategic Development of North Sea Grid Infrastructure to Facilitate Least-Cost Decarbonisation. Imperial College London; 2014.
[11] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. doi:10.1016/j.rser.2014.02.003.
[12] Ventosa M, Baíllo Á, Ramos A, Rivier M. Electricity market modeling trends. Energy Policy 2005;33:897–913. doi:10.1016/j.enpol.2003.10.013.
[13] Herbst A, Toro F, Reitze F, Jochem E. Introduction to energy systems modelling. 2012.
[14] ENTSO-E European Network of Transmission System Operators for Electricity. Fostering Electricity transmission investments to achieve Europe´s energy goals: Towards a future-looking regulation. 2014.
[15] EC European Commission. Energy Union Package - A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy. 2015.
[16] van Renssen S. EU announces Treaty change to realise Energy Union. EnergyPost.eu 2015. http://www.energypost.eu/eu-announces-treaty-change-realise-energy-union/ (accessed April 6, 2015).
[17] E3G. North Seas Grid Project Pipeline Analysis. E3G; 2013.
[18] Meeus L. Offshore Grids for Renewables - Do We Need a Particular Regulatory Framework? Florence School of Regulation: 2014.
[19] Sinclair Knight Merz. DECC - Research into GB offshore electricity transmission development. A comparative assessment with key countries. 2012.
[20] RECHARGE. TenneT to build Dutch offshore grid 2014.
[21] reNews. Belgium OKs offshore wind grid 2014.
[22] van Dam KH, Nikolic I, Lukszo Z. Agent-Based Modelling of Socio-Technical Systems. Springer; 2013.
[23] De Vries LJ. Securing the public interest in electricity generation markets. The myths of the invisible hand and the copper plate. Technische Universiteit Delft, 2004.
[24] Pérez-Arriaga IJ, editor. Regulation of the Power Sector. 2013.
[25] EPEX European Power Exchange. EUPHEMIA: Description and functioning 2014.
[26] ACER Agency for the Cooperation of Energy Regulators, CEER Council of European Energy Regulators. Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2013. 2014.
[27] Latorre G, Cruz RD, Areiza JM, Villegas A. Classification of publications and models on transmission expansion planning. Power Syst IEEE Trans On 2003;18:938–46. doi:10.1109/TPWRS.2003.811168.
[28] von Hirschhausen C. Developing a Supergrid. In: Moselle B, Padilla J, Schmalensee R, editors. Harnessing Renew. Energy Electr. Power Syst. Theory Pract. Policy, 2010.
[29] Morales JM, Conejo AJ, Madsen H, Pinson P, Zugno M. Integrating Renewables in Electricity Markets - Operational Problems. vol. 205. 2014.
[30] ENTSO-E European Network of Transmission System Operators for Electricity. Offshore Transmission Technology. 2012.
[31] Grasselli U, Quacquarelli M, Gentili S. Development of Offshore Grid: State of the art of technology and solutions. Proc. 5th Int. Conf. Dev. Energy Environ. Econ. DEEE 14, 2014.
[32] Cole S, Martinot P, Rapoport S, Papaefthymiou G, Gori V. Study of the Benefits of a Meshed Offshore Grid in the Northern Seas Region. European Commission; 2014.
[33] Sinclair Knight Merz. Research into GB offshore electricity transmission development. Lessons Learned. Department of Energy and Climate Change; 2012.

Pre-print – Published article at the Renewable & Sustainable Energy Reviews - 10.1016/j.rser.2016.01.112

[34] Markard J. Transformation of Infrastructures: Sector Characteristics and Implications for Fundamental Change. J Infrastruct Syst 2011;17:107–17. doi:10.1061/(ASCE)IS.1943-555X.0000056.

[35] Egerer J, von Hirschhausen C von, Kunz F. Planning the Offshore North and Baltic Sea Grid Technical and Socio-Economic Analysis of Different Pathways. 2012.

[36] Lévêque F, Meeus L, Azevedo I, Saguan M, Glachant J-M. Offhore Grids: Towards a Least Regret EU Policy. European University Institute; 2012.

[37] Roeben V. Governing Shared Offshore Electricity Infrastructure in the Northern Seas. Int Comp Law Q 2013;62:839–64.

[38] Woolley O. Governing a North Sea Grid Development: The Need for a Regional Framework Treaty. Compet Regul Netw Ind 2013;14.

[39] Gaventa J, Bergamaschi L, Ryan E. Delivering the North Seas Grid - Towards a Regional Free Trade Zone of Electricity 2015.

[40] Flynn B. Understanding the Politics of Europe’s Offshore Electricity Grids: an ambiguous affair?, 2014.

[41] Müller HK. Developing a Transnational Offshore Grid: Legal Challenges and Possible Solutions 2014.

[42] Piria R, Zavolas L. Priorities in the North Sea Grid Debate. SEFEP; 2012.

[43] Busch S, Liebmann L, Resch G, Nysten J, Gephart M. Cooperation under the RES Directive - Case studies: Joint Support Schemes. European Commission; 2014.

[44] NSCOGI The North Seas Countries’ Offshore Grid Initiative. Discussion Paper 2: Integrated Offshore Networks and The Electricity Target Model. NSCOGI; 2014.

[45] NSCOGI The North Seas Countries’ Offshore Grid Initiative. Discussion Paper: Possible Market Arrangements for Integrated Offshore Networks. 2013.

[46] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. doi:10.1016/j.apenergy.2009.09.026.

[47] Foley AM, Ó Gallachóir BP, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. 3rd Int Conf Sustain Energy Environ Prot SEEP 2009 2010;35:4522–30. doi:10.1016/j.energy.2010.03.057.

[48] Bazmi AA, Zahedi G. Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review. Renew Sustain Energy Rev 2011;15:3480–500. doi:10.1016/j.rser.2011.05.003.

[49] ENTSO-E European Network of Transmission System Operators for Electricity. Regional Investment Plan 2014 - North Sea Region. 2014.

[50] NSCOGI The North Seas Countries’ Offshore Grid Initiative. Initial Findings. NSCOGI; 2012.

[51] Egerer J, Kunz F, Hirschhausen C von. Development scenarios for the North and Baltic Seas Grid – A welfare economic analysis. Util Policy 2013;27:123–34. doi:10.1016/j.jup.2013.10.002.

[52] Haileselassie TM, Uhlen K. Power System Security in a Meshed North Sea HVDC Grid. Proc IEEE 2013;101:978–90. doi:10.1109/JPROC.2013.2241375.

[53] Pinto RT. Multi-Terminal DC Networks: System Integration, Dynamics and Control. 2014.

[54] Holttinen H, editor. Expert Group Report on Recommended Practices: 16. Wind Integration Studies 2013.

[55] Huertas-Hernando D, Svendsen HG, Warland L, Trötscher T, Korpås M. Analysis of grid alternatives for North Sea offshore wind farms using a flow-based market model. Energy Mark EEM 2010 7th Int Conf Eur 2010:1–6. doi:10.1109/EEM.2010.5558725.

[56] Trötscher T, Korpås M. A framework to determine optimal offshore grid structures for wind power integration and power exchange. Wind Energy 2011;14:977–92. doi:10.1002/we.461.

[57] Tröster E, Glotzbac L, Ackerman T, Fürsc M, Jägeman C, Nagl S, et al. The Importance of Grid Expansion in a High Wind Penetration Scenario for Europe until 2050, 2011.

[58] ENTSO-E European Network of Transmission System Operators for Electricity. Regional Investment Plan North Sea - Final. 2012.

[59] Ciupuliga AR, Gibescu M, Pelgrum E, van der Meijden MAMM, Kling WL. A market-based investigation of large-scale Renewable Energy integration in Northwestern Europe. Power Energy Soc Gen Meet 2012 IEEE 2012:1–8. doi:10.1109/PESGM.2012.6345357.

[60] Ciupuliga AR. Transmission Expansion Planning under Increased Uncertainties - Towards Efficient and Sustainable Power Systems. Technische Universiteit Delft, 2013.

[61] Rodrigues S, Bauer P, Wiggelinkhuizen E, Pierik J. Optimization of North Sea Transnational Grid Solutions. 2013.

[62] Drees T, Linnemann C, Schuster H, Moser A, Panke T, Burstedde B. Technical and Economic Evaluation of a North Sea Grid, 2013.

[63] Strbac G, Vasilakos Konstantinidis C, Moreno R, Konstantelos I, Papadaskalopoulos D. It’s All About Grids: The Importance of Transmission Pricing and Investment Coordination in Integrating Renewables. Power Energy Mag IEEE 2015;13:61–75. doi:10.1109/MPE.2015.2418075.

[64] Cole S, Martinot P, Rapoport S, Papaefthymiou G. Cost-benefit analysis of a coordinated grid development in the North Sea. PowerTech 2015 IEEE Eindh 2015:1–5. doi:10.1109/PTC.2015.7232385.

[65] Buatois A, Gibescu M, Rawn BG, van der Meijden MAMM. Analysis of North Sea Offshore Wind Power Variability. Resources 2014;3:454–70. doi:10.3390/resources3020454.

[66] Torbaghan SS, Muller H, Gibescu M, van der Meijden M, Roggenkamp M. Impact of wind energy support schemes on the development of an offshore grid in the North Sea. PES Gen Meet Conf Expo 2014 IEEE 2014:1–5. doi:10.1109/PESGM.2014.6939081.

[67] Azari D, Torbaghan SS, Gibescu M, van der Meijden MAMM. The impact of energy storage on long term transmission planning in the North Sea region. North Am Power Symp NAPS 2014 2014:1–6. doi:10.1109/NAPS.2014.6965402.

[68] Jaehnert S, Wolfgang O, Farahmand H, Völler S, Huertas-Hernando D. Transmission expansion planning in Northern Europe in 2030—Methodology and analyses. Energy Policy 2013;61:125–39. doi:10.1016/j.enpol.2013.06.020.

[69] van der Meer AA, Ndreko M, Bos JA, Gibescu M, van der Meijden MAMM, Kling WL. Stability assessment of VSC-HVDC connected large-scale offshore wind power: A North-Sea region case study. PowerTech 2015 IEEE Eindh 2015:1–6. doi:10.1109/PTC.2015.7232787.

[70] Torbaghan SS, Gibescu M, Rawn B, Van der Meijden M. A market-based transmission planning for HVDC grid—case study of the North Sea. Power Energy Soc Gen Meet 2015 IEEE 2015:1–1. doi:10.1109/PESGM.2015.7286438.

[71] Torbaghan SS, Müller HK, Gibescu M, van der Meijden M, Roggenkamp M. The legal and economic impacts of implementing a joint feed-in premium support scheme on the development of an offshore grid. Renew Sustain Energy Rev 2015;45:263–77. doi:10.1016/j.rser.2015.01.058.

[72] Uddin Ahmad Chowdhury N, Yanushkevich A. Power flow analysis of meshed AC-DC super grid. PowerTech 2015 IEEE Eindh 2015:1–6. doi:10.1109/PTC.2015.7232399.

[73] Chondrogiannis S, Blanco MP. Market Integration Scheme of a Multi-Terminal HVDC Grid in the North Seas. Power Syst IEEE Trans On 2015;PP:1–8. doi:10.1109/TPWRS.2015.2465860.

[74] EWEA European Wind Energy Association. Wind Energy Scenarios for 2020. 2014.

[75] Midttun A, Ruohonen T, Piria R. Norway and the North Sea Grid - Key Positions and Players in Norway, from a Norwegian Perspective. Smart Energy for Europe Platform; 2012.

[76] Saltelli A, Annoni P. How to avoid a perfunctory sensitivity analysis. Environ Model Softw 2010;25:1508–17. doi:10.1016/j.envsoft.2010.04.012.