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Doctoral Thesis

EXPANSION GOVERNANCE OF THE INTEGRATED NORTH SEAS OFFSHORE GRID

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Expansion Governance of the Integrated North Seas Offshore Grid

João GORENSTEIN DEDECCA

Expansion Governance of the Integrated North Seas Offshore Grid

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
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by

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The doctoral research has been carried out in the context of an agreement on joint doctoral supervision between Comillas Pontifical University, Madrid, Spain, KTH Royal Institute of Technology, Stockholm, Sweden, and Delft University of Technology, the Netherlands.

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Keywords: Energy Union, expansion planning, governance, HVDC, myopic optimization, North Seas, offshore grid, offshore wind, simulation

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SETS Joint Doctorate

The Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies, SETS Joint Doctorate, is an international programme run by six institutions in cooperation:

- Comillas Pontifical University, Madrid, Spain
- Delft University of Technology, Delft, the Netherlands
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This thesis is a part of the examination for the doctoral degree. The invested degrees are official in Spain, the Netherlands and Sweden respectively.

SETS Joint Doctorate was awarded the Erasmus Mundus excellence label by the European Commission in year 2010, and the European Commission's Education, Audiovisual and Culture Executive Agency, EACEA, has supported the funding of this programme.

Abstract

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The expansion of offshore power transmission and generation in the North Seas of Europe is accelerating rapidly. This is due to several drivers, including the decarbonization and reform of the European power system, and innovations in offshore wind and high-voltage direct current transmission. So far, this European North Seas offshore grid is composed of conventional transmission lines, which perform the interconnection of onshore power systems and the wind farm connection functions separately. An integrated offshore grid is an innovative concept where some of the transmission lines perform simultaneously both the interconnection and connection functions. Earlier research leveraging optimization approaches already demonstrated that such an integrated offshore grid can provide socio-economical, technical and environmental benefits.

The offshore grid is characterized by its multiplicity of actors, working in several levels, from the European to the sub-national. This makes governance the only adequate decision-making mode to manage the grid expansion towards more integration. Governance combines hierarchies, markets and networks in order to guide decision-making in a networked multi-level, multi-actor system. The expansion governance of the offshore grid can be analyzed according to six building blocks: meta-governance, planning, financing, ownership, pricing and operation. Previous studies have identified important barriers in these building blocks for the development of an integrated offshore grid. These comprise the difficulties in the site planning and development of integrated projects, the allocation of costs and benefits among actors, and the compatibilization of national support schemes to offshore wind.

This research applies an exploratory approach to expansion governance to understand how the offshore grid can be managed towards more integration in the presence of these barriers. Therefore, it does not prescribe investments in specific offshore wind farms and transmission corridors. This approach combines energy systems modeling and regulatory analysis to focus on the management of investments in offshore assets, which are central to developing an integrated grid.

The Offshore Grid Exploratory Model (OGEM) was developed in this thesis to endogenously represent integrated governance barriers: the complexity of planning integrated lines and the interests of individual North Seas countries. OGEM confirms that an integrated offshore grid is beneficial to Europe. However, these benefits are highly dependent on the e-Highway2050 scenarios used, and asymmetrically distributed between countries and actor groups. Governance barriers (represented as model constraints) lead to a modest reduction in benefits, and do not change the distribution asymmetry.

The impact of the barriers is more pronounced regarding investment changes in transmission technologies and integrated lines. They increase path dependence and hinder the deployment of multiterminal HVDC lines. Also, the location and potential of offshore wind interacts with investments in offshore transmission, both of which can change radically in the presence of governance barriers.

The impact of these barriers on the offshore expansion pathways allows to recommend design principles for governance frameworks of offshore investments. These comprise the need for: a comprehensive expansion candidate portfolio including both non-integrated multiterminal HVDC and integrated projects; to consider the interrelation of expansion periods in planning; and to consider different rates of innovation for transmission technologies.

In parallel, the Clean Energy Package is analyzed for the changes they bring to the European regional governance of offshore expansions. Five challenges are identified. The first two deal with the interaction of the governance structure of the European and national levels with the regional one. Then, the third challenge deals with the participation of the United Kingdom and Norway in the European expansion governance. On the other hand, the las two challenges concern specific governance building blocks. The planning challenge indicates that the regional planning of the offshore grid is dependent on national development plans, which in their turn must consider national interests. And the pricing and financing challenge indicates that cost allocation for Projects of Common Interest rigidly precedes the application for financing, invalidating the cost allocation in case the application is unsuccessful. Importantly, these challenges are largely unaddressed by the Energy Union reform.

The thesis concludes with a number of policy recommendations. They concern meta-governance and the need for capacity building at the regional level. Then, multiple recommendations cover planning. Beyond following the design principles above, the planning challenge needs to be solved. Also, planning models and data should move towards open-modeling approaches which would facilitate the consideration of a broader candidate portfolio. Regarding financing and pricing, the regulation should foster more anticipatory investments than the current practice, and the Projects of Common Interest cost allocation and funding challenge should be solved. These recommendations constitute specific changes to the European expansion governance which would significantly improve the playing field for an integrated offshore grid.

Samenvatting

Auteur: João Gorenstein Dedecca

Titel Proefschrift: Expansion Governance of the Integrated North Seas Offshore Grid

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Trefwoorden: bijziend optimalisatie, Energie-Unie, governance, HVDC, Noordzeeën, offshore netwerk, simulatie, uitbreidingsplanning, wind op zee

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De ontwikkeling van offshore elektriciteitsproductie en -transmissie van elektriciteit in de Noordzee van Europa versnelt. Dit komt door verschillende factoren, zoals de trend naar decarbonisatie van het energiesysteem, hervormingen in de Europese elektriciteitsmarkt en innovaties in de technologie voor offshore windproductie en gelijkstroomtransport.

Tot dusverre bestaat het offshore elektriciteitsnet in de Noordzee uit conventionele hoogspanningskabels, die de interconnectie van (onshore) energiesystemen en de aansluiting van de turbines op zee separaat uitvoeren. Een geïntegreerd offshore netwerk is een innovatief concept waarbij sommige transmissielijnen zowel een interconnectie- als een verbindingsfunctie hebben.

Het offshore netwerk wordt gekenmerkt door zijn veelheid aan actoren, die op verschillende niveaus, van Europees tot subnationaal, werken en wel vaak los van elkaar. Onderzoek met eenvoudige optimalisatiemodellen uit het verleden laat al zien dat een geïntegreerd offshore netwerk sociaal-economische, technische en milieuvoordelen biedt. Daarom is een verbeterde governance noodzakelijk om een netuitbreiding met meer integratie te sturen. Deze governance loopt echter tegen verschillende barrières aan op verschillende niveaus: van belemmeringen in de metagovernance tot barrières in de planning en operatie.

Dit onderzoek verkent de governance van netuitbreiding om te onderzoeken hoe het offshore elektriciteitsnet het beste kan worden gestuurd naar meer integratie. De aanpak combineert technische energiesysteemmodellering met een analyse van de reguleringskaders en richt zich op de investeringen in de offshore assets. Het laatstgenoemde is namelijk bepalend voor de ontwikkeling van een geïntegreerd netwerk.

Het voor dit onderzoek ontwikkelde model, het Offshore Grid Exploratory Model (OGEM), bevat naast technisch-economische componenten ook randvoorwaarden voor de geïntegreerde governance. Deze laatste representeren de complexiteit van de planning en de coördinatie van de verschillende belangen van afzonderlijke Noordzeelanden. Het model geeft inzicht in de impact van deze randvoorwaarden

en beperkingen op de geïntegreerde ontwikkeling van het offshore grid. Hieruit worden vervolgens ontwerpprincipes afgeleid voor de governance van offshore investeringen.

Ten slotte wordt de impact van het Clean Energy Package van de Europese Commissie op de governance van investeringen in het offshore elektriciteitsnet geanalyseerd. Er worden vijf uitdagingen geïdentificeerd die, voor het overgrote deel, niet worden aangepakt door de recente hervorming van de Energie-Unie.

Op basis van het onderzoek worden een aantal beleidsaanbevelingen gedaan voor het (meta)bestuur, de planning, de financiering en de prijsstelling voor offshore netuitbreiding. Deze omvatten onder andere pro-actieve planning en projectportfolio ontwikkeling op regionaal niveau. Implementatie van deze aanbevelingen voor de Europese governance van netontwikkeling zal het speelveld voor een geïntegreerd offshore elektriciteitsnet aanzienlijk verbeteren.

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Resumen

La expansión de la transmisión y generación eléctrica en los mares del norte de Europa se está acelerando rápidamente. Esto se debe a varios factores, entre ellos la descarbonización y la reforma del sistema eléctrico europeo, y las innovaciones en la energía eólica marina y en la transmisión DC.

Hasta el momento, esta red marítima del Mar del Norte de Europa está compuesta por líneas de transmisión convencionales, que realizan las funciones de interconexión de los sistemas eléctricos en tierra y de conexión del parque eólico por separado. Una red offshore integrada es un concepto innovador donde algunas de las líneas de transmisión realizan las funciones de interconexión y conexión simultáneamente. Estudios utilizando modelos de optimización indican que una red integrada proporciona beneficios socio-económicos, técnicos y ambientales.

La red offshore se caracteriza por su multiplicidad de actores, que trabajan en varios niveles, desde el europeo hasta el subnacional. Esto hace que la gobernanza sea la única forma de gestionar la expansión de la red hacia una mayor integración. La gobernanza de la expansión de la red offshore se enfrenta a varias barreras interrelacionadas en muchos bloques de la gobernanza, desde metagobernanza hasta planificación y operación.

Esta investigación aplica un enfoque exploratorio a la gobernanza de la expansión para comprender cómo se puede gestionar la red offshore para lograr una mayor integración. Este enfoque combina el modelado de los sistemas eléctricos y el análisis regulatorio de la gestión de las inversiones en activos offshore, que son fundamentales para desarrollar una red integrada.

El Offshore Grid Exploratory Model (OGEM) introduce restricciones integradas de gobernanza, que representan la complejidad coordinación de los intereses de los países del Mar del Norte y de planificación. El impacto de las restricciones permite recomendar principios de diseño para los marcos de gobernanza para las inversiones offshore.

Paralelamente, se el Clean Energy Package por su impacto en la gobernanza de la expansión offshore. Se identifican cinco desafíos, que no son resolvidos por la reforma de la Unión de la Energía.

Finalmente, se hacen recomendaciones de política en los bloques de gobernanza de metagobernanza, planificación, financiamiento y precificación. Estos incluyen la planificación proactiva y el desarrollo de la cartera de proyectos a nivel regional, y la consideración de la interacción de líneas HVDC multiterminal con proyectos integrados. Esas recomendaciones constituyen cambios específicos en la gobernanza europea de la expansión que mejorarían significativamente el campo de juego para una red integrada offshore.

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Språk: Engelska

Nyckelord: Energiunion, expansionsstyrning, styrning, HVDC, myopisk optimering, Nordsjön, offshore-nätet, offshore vindkraft, simulering

Sammanfattning

Utbyggnaden av havsbaserad kraftöverföring- och generering i Nordsjön i Europa ökar snabbt. Detta beror på flera faktorer, bland annat dekarboniseringen och reformeringen av det europeiska kraftsystemet och innovationer inom den vindkraftsbaserade och högspända likströmsöverföringen offshore.

Än så länge består detta europeiska havsbaserade vindkraftsnät i Nordsjön av konventionella transmissionsledningar, vilka utför separata sammankopplingar av landbaserade kraftsystem och vindkraftparkens anslutningssystem. Ett integrerat havsbaserat vindkraftsnät är ett innovativt koncept där vissa av transmissionsledningarna samtidigt utför både sammankopplings- och anslutningsfunktioner. Forskning som utnyttjar optimeringsmetoder har visat att ett dylikt integrerat havsbaserat vindkraftsnät kan tillhandahålla socioekonomiska, tekniska och miljömässiga fördelar.

Det havsbaserade vindkraftsnätet karakteriseras av dess många aktörer, vilka arbetar på flera nivåer, från europeisk nivå till subnationell. Detta gör att styrning är den enda lämpliga metoden för beslutsfattande för att hantera utbyggnaden av vindkraftsnätet mot mer integration. Styrningen av utbyggnaden av det havsbaserade vindkraftsnätet står inför flera interrelaterade hinder inom många viktiga styrningsområden, från metastyrning till planering och drift.

Denna forskning tillämpar ett utforskande tillvägagångssätt på styrning av vindkraftsutbyggnad för att förstå hur det havsbaserade vindkraftsnätet kan styras mot mer integration. Detta tillvägagångssätt kombinerar modellering av energisystem och regulatorisk analys för att fokusera på förvaltningen av investeringar i offshorekapital, vilket är centralt för att utveckla ett integrerat nät.

Forskningsmodellen för havsbaserade vindkraftsnät (OGEM) introducerar integrerade styrningshinder, vilka representerar komplexiteten i planeringen av integrerade ledningar och intressen hos enskilda Nordsjöländer. Effekterna av dessa begränsningar gör det möjligt att rekommendera designprinciper för styrningsramverk för offshoreinvesteringar.

Parallellt med detta analyseras effekterna av de nuvarande förslagen från Energiunionen på styrningen av utbyggnaden av havsbaserade vindkraftsnät. Tre dilemman och två paradoxer kan identifieras, där de förra täcker alla viktiga styrningsområden, medan de senare inbegriper specifika konflikter inom vissa områden. Dessa dilemman och paradoxer lämnas i stor utsträckning obesvarade i Energiunionens reform.

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I had a (more or less) stable path towards graduation. That is also in no small part due to the support I had during the whole Ph.D. from family, friends and colleagues. As well as due to a privileged background, and some luck here and there, which in no way diminishes my appreciation of the support received. Adapting the customary preface , I am indebted to all for their invaluable help in life and in this thesis; any errors which remain are my sole responsibility.

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Finally, gratitude goes both ways: I hope to have made the life and work of those around me more enjoyable and interesting. Little more is needed than following that simple recipe, but one needs to do it often.

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Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
BI	British isles
CAPEX	Capital expense
CBCA	Cross-border cost allocation
CCGT	Combined cycle gas turbine
CE	Continental Europe
CEF	Connecting Europe Facility
CCS	Carbon capture and storage
CSC	Current-source converter
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
HVAC	High-voltage alternated current
HVDC	High-voltage direct current
IC	Interconnector
LCoE	Levelized cost of energy
NDP	National development plan
NRA	National regulatory authority
NSB	Net social benefits
NPV$_a$	Absolute net present value
NPV$_r$	Net present value ratio
NSCOGI	North Seas Countries' Offshore Grid Initiative
O&M	Operation and maintenance
OGEM	Offshore Grid Exploratory Model
OPEX	Operating expense
PCI	Project of Common Interest
PV	Photovoltaic
RES	Renewable energy source
RgIP	Regional Investment Plan
SC	Scandinavia
TEN-E	Trans-European Networks for Energy
TEP	Transmission expansion planning
TSO	Transmission system operator
TYNDP	Ten-Year Network Development Plan
VSC	Voltage source converter

1 Introduction

In recent years several developments have driven the expansion of offshore power transmission and generation in the North Seas of Europe: the regulatory reform of the European system with increased market and renewable energy sources integration, the deployment of offshore wind, and innovations in direct current power transmission [1,2].

First, for some decades now several electricity markets worldwide have been restructured. This restructuring consists in a shift away from centralized investment and operation to market-based decentralized decision-making with multiple actors [3]. These new market designs usually involve the institution of new actors such as regulators, and the separation (unbundling) of power transmission and distribution from other activities. Decentralization leads to many challenges, including guaranteeing adequate transmission and generation investments, and coordinating these with energy, environmental and industrial policies.

The European Union 2020 climate and energy package established a binding target for renewable energy in each Member State final energy consumption. This has driven the deployment of renewable energy sources of electricity in Europe. Pushing this further, the 2030 Climate and Energy Policy Framework aims at renewable energy to compose at least 32% of energy consumption of the European Union. Finally, to achieve pledges the European power sector must reach almost complete decarbonization by 2050 [4–6].

To achieve these and other energy and climate goals, the European Union is forming the Energy Union. This holistic approach aims to integrate the European energy and climate policies to attain these policies' targets, focusing on five Energy Union dimensions [7]. It includes a governance process for the streamlined planning, monitoring and reporting of efforts of Member States. This to ensure 'a coordinated and coherent implementation of the Energy Union Strategy across its five dimensions' to achieve energy and climate targets [4]. Several of the 2030 targets are not binding at a national level, and the necessity of specific support schemes for renewable energy are still a subject of debate [8]. Completing the Internal Energy Market is another main goal of the European energy and climate policy. In order to achieve this, the European Union aims for countries to achieve a 15% interconnection level of their power systems by 2030, further driving the expansion of power transmission in Europe [9].

Then, the cooperation of industry, academia and governments has resulted in sharp cost reductions for offshore wind, as reflected in the recent auction prices [10]. In five years the levelized cost of offshore wind has fallen from more than 150 to less than 80€/MWh [11]. The third and final driver for offshore investments are innovations in power transmission, especially concerning AC/DC voltage-source converters, VSC [12]. The technology provides operational advantages when compared to the older current-source converter technology, such as improved active power control and the capability to provide reactive power control. Furthermore, these converters enable multiterminal high-voltage direct current (HVDC) grids, where AC/DC converters are placed only at points of power injection or withdrawal. This provides the opportunity for investment savings through the deployment of a reduced number of these converters and the corresponding transmission cables.

1.1. The North Seas offshore grid

These drivers have already led to the development of an offshore power system: at the end of 2017 Europe had 15.8 GW of installed offshore wind capacity and several offshore interconnectors [13,14]. Moreover, WindEurope [15] estimates in its central scenario that European offshore wind will reach 70 GW by 2030. Also, the ENTSO-E [16] regional investment plan for the North Sea includes up to 28 GW in new offshore interconnectors until 2030.

Therefore, there already exists a North Seas offshore grid which combines the interconnection of onshore power systems (in Scandinavia, the British Isles and Continental Europe) with the connection of offshore wind farms to these systems. The simultaneous expansion of offshore generation and transmission provides the opportunity to develop integrated projects (also called hybrid), which combine these two functions.

The expansion of power systems leads to benefits in the categories of market integration, climate and the environment, security of supply, European integration, and industrial competitiveness & innovation [9]. These benefits also apply to the offshore expansion of transmission and generation in the North Seas, especially with integrated projects. The North Seas offshore grid is for this reason a priority corridor for the European Union [17]. However, there are still uncertainties on the magnitude of these benefits and how to adequately quantify them. Moreover, there are significant barriers to the integrated North Seas offshore grid concerning the European and national regulations, the technology and the interests of countries and actors [1].

The increasing penetration of intermittent renewable energy sources in modern power systems requires more system flexibility, to which power transmission can contribute [18]. In order to increase transmission investments, unbundled power systems worldwide are going through regulatory reforms centralizing expansion planning at higher decision-making levels, often the regional one. This can be observed for example in the different energy and infrastructure packages implemented in Europe since 2009, or in the ruling for interregional transmission expansion planning in the US [5,19].

A pivotal activity to realize investments in offshore transmission and generation is expansion planning: identifying the most adequate investments in generation and transmission to guarantee the future system reliability given certain energy and climate policy objectives [20]. Expansion planning is one of the building blocks of expansion governance: the decision-making process on transmission and generation investments combining hierarchical and non-hierarchical institutions in a networked multi-level, multi-actor system. [21]. More recently, changes are being made to the European expansion governance framework, as part of the Energy Union reform of European energy and climate governance and power market operation [22]. However, this reform has attracted criticism for either too much or too little centralization, or for not addressing the decision-making for investments at the regional level [23,24]. This comes at a time when cooperation initiatives are restarted at the regional level of the North Seas, with the North Seas Energy Cooperation as the main example [25].

Furthermore, the expansion of power systems is not immediate, and happens rather gradually and guided by periodic expansion plans, for example every two years in Europe [5]. Continuous investment in generation and transmission projects in an already-existing power system creates an expansion pathway leading to a final, different power system. Investment decisions can be significantly affected by previous ones, so expansion pathways are characterized by path dependence. This adds a dynamic character to expansion governance, already distinguished by multiple building blocks of decision-making in a multi-actor, multi-level system.

1.2. Problem statement

There are thus developments which affect the expansion governance of the offshore grid, be they specific to it or general to the European energy system. The offshore grid is continuously expanding, with already many offshore interconnectors and wind farms being installed in the North Seas. Thus, the offshore grid expansion will combine integrated and conventional assets (transmission lines and wind farms). However, there is a multiplicity of actors on all levels from the European to the sub-national. Also, there are uncertainties surrounding the European power system and the offshore grid such as regarding the speed of HVDC transmission innovations. These factors make it impossible for any single actor to determine the offshore grid expansion pathway.

Designing an appropriate offshore expansion governance framework for the North Seas involves addressing several barriers. As detailed in section 2.4, these barriers can be analysed through the governance building blocks: meta-governance, planning, ownership, financing, pricing and operation [26]. Planning and pricing barriers such as the costs and benefits allocation, the support schemes for offshore wind and the site planning and development of integrated projects are often indicated as significant obstacles to the integrated offshore grid [27–29]. This governance framework is continuously evolving, influenced by the cooperation of North Seas countries and the overall European expansion governance framework.

Research indicates that an integrated offshore grid provides greater benefits than a conventional one (chapter 3), that which is confirmed in chapters 4 and 5. Given the benefits of an integrated offshore grid and the barriers to the offshore expansion governance, the central question of this thesis is how actors can govern these expansion pathways towards more integration. This involves three decision-making aspects. The first aspect is which actors affect the expansion pathways, that is, which are the relevant decision-making actors influencing the expansion of the offshore grid. The second is how this decision-making should happen in order to enable an integrated offshore grid. The third and final aspect is at which level this decision-making should take place, in order to balance the advantages and disadvantages of the possible levels (European, regional and national).

1.3. Research questions

Given the problem statement, the main research question of this thesis is:

- How can the expansion pathway of the North Seas offshore grid be governed towards more integration?

This research question thus focuses on the integrated nature of the offshore grid. It acknowledges that the expansion pathway will be a combination of integrated and non-integrated, conventional assets, and that it cannot be fully governed by any single actor in Europe. In order to address the research question, this thesis formulates the following subordinate research questions:

- Research question 1: How do actors in the European power system affect the offshore expansion pathway?
- Research question 2: Which factors affect offshore expansion pathways as informed by offshore grid models?
- Research question 3: How do governance barriers affect expansion pathways towards an integrated offshore grid?
- Research question 4: How adequate is the current European expansion governance framework to enable the integrated offshore grid?

1.4. Methodology

The thesis applies multiple methods to address the research questions: a theory on the governance of expansion pathways, a review of offshore grid models, and quantitative and qualitative analyses, as indicated in Figure 7.1.

To address the subordinate research question 1, first the main concepts used throughout the thesis are presented. These enable the discussion of how the expansion pathway of the offshore grid is determined through the management of investments in generation and transmission. Finally, governance at the regional level is indicated as the most adequate decision-making mode for this investment management. These aspects are covered in chapter 2.

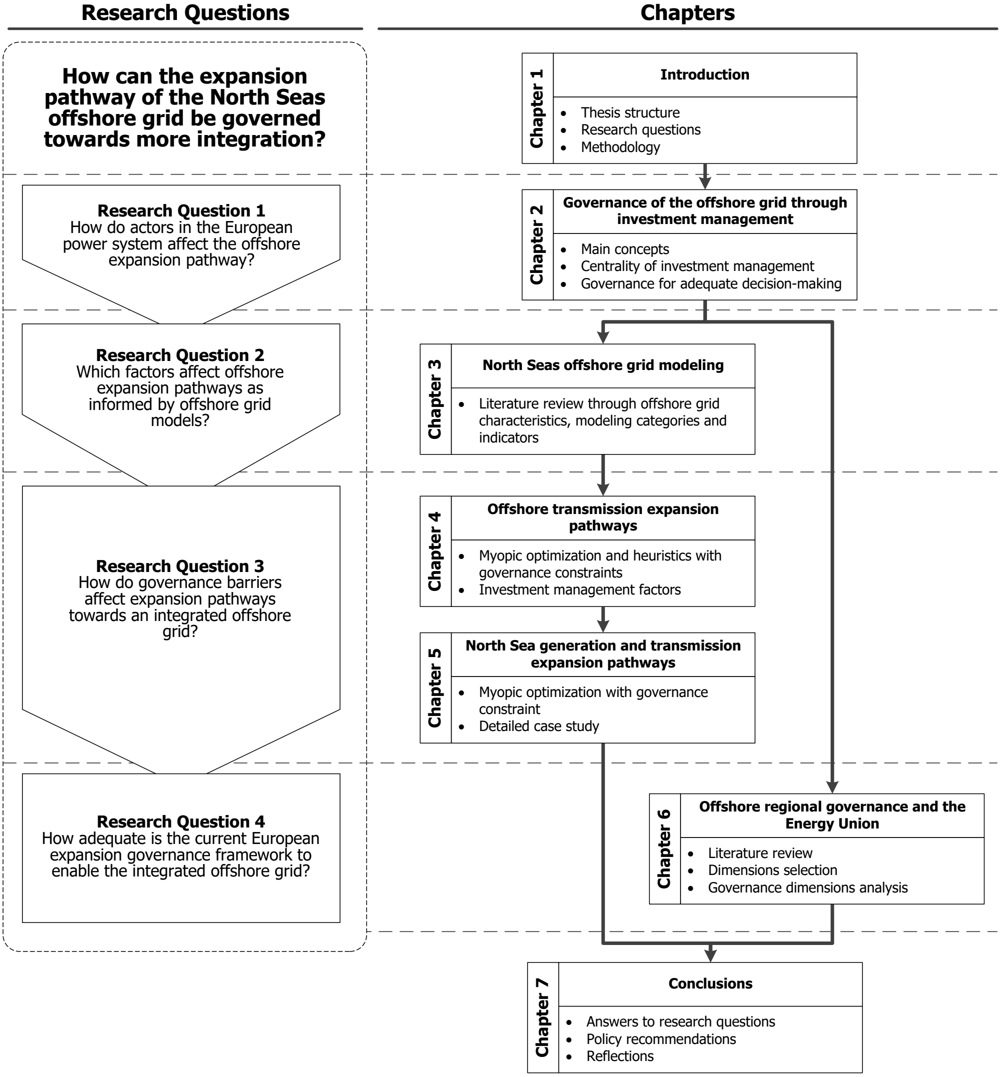

Figure 1.1: Thesis structure

The subordinate research question 2 leverages offshore grid models to understand factors for expansion pathways. Models allow for the explicit and detailed representation of energy systems and their behavior. They go beyond the capabilities of human cognition and are applicable to multiple case studies. Thus, a review of offshore grid models is conducted, identifying two central gaps. First, current offshore grid modeling predominantly uses an optimization approach, there being thus a lack of simulation models. Second, there is a lack of offshore grid models which endogenously represent governance barriers. In this way the review indicates both how existing models have contributed to understanding factors for the expansion pathways of the offshore grid and which are the current modeling gaps. This is presented in chapter 3.

To address the subordinate research question 3 a new open-source myopic optimization model for offshore expansion which includes novel governance barriers was developed. The Offshore Grid Exploratory Model (OGEM) addresses the offshore grid modeling gaps identified in the 2nd subordinate research question and is used in case studies in chapters 4 and 5. Chapter 4 develops a transmission expansion conceptual case study on an offshore system, identifying several factors which affect the investment management. Chapter 5 further develops OGEM to conduct a detailed case study on generation and transmission expansion of the North Seas offshore grid. It focuses on the endogenous representation of the governance barriers and the analysis of specific investment management factors, such as the interaction of transmission line technologies and types.

Next, to attend to the 4th subordinate research questions a qualitative analysis of the regional offshore expansion governance framework of the European Union is conducted. This analysis complements the quantitative analysis enabled by OGEM, and evaluates the ability of the governance framework to enable an integrated offshore grid. It does so considering how this framework will be once the main regulatory package of the Energy Union (the Clean Energy for All Europeans Package) is implemented. Chapter 6 presents this qualitative analysis.

Chapter 7 finally summarizes the answers to the research questions, providing policy recommendations for enabling integrated expansion pathways for the European North Seas offshore grid. The policy recommendations cover the governance building blocks of meta-governance, planning, and financing & pricing. The reflections presented in that chapter also contextualize the research conducted into a broader, more complex environment.

2 Governance of the offshore grid through investment management[a]

2.1. Introduction

The offshore grid will significantly contribute to the European energy transition, supporting the attainment of the 2050 European energy and climate goals [1]. However, there is a large uncertainty on diverse aspects. These include the regulatory framework for offshore investments and operation, the generation matrix structure (i.e. the energy sources mix), and the deployment of demand-side management and storage technologies [31,32]. Coupled with the complexity of the European power system, it is impossible for any single European decision-maker to control the transition to a decarbonized energy system. What can be done is to govern the evolution of the energy system and the North Seas offshore grid towards more desired pathways.

This chapter therefore presents the concepts and arguments which address the first subordinate research question: how do actors in the European power system affect the offshore expansion pathway? The answer to this question bases the expansion pathway analyses of chapters 4 and 5 and the regional offshore governance analysis of chapter 6.

Section 2.2 defines the North Seas offshore grid, presenting its characteristics, the benefits it brings to Europe and the main drivers for its current development. As seen in chapter 1, it is impossible for any single decision-maker to determine the expansion pathway of the grid. Given this, section 2.3 indicates how this expansion can be managed through investments in transmission and generation assets in the presence of path dependence. Due to the offshore grid characteristics, decision-making on expansion pathways of the grid needs to be made through governance, which is covered in section 2.4.

2.2. The North Seas offshore grid

The North Sea offshore grid is defined as

> the power system in the North Sea combining offshore power generation (particularly from renewable sources), offshore loads and transmission lines of different technologies.

Offshore conventional generation from fossil fuels and offshore loads (especially oil and gas platforms) may participate but are not as important a driver for the offshore grid as offshore generation from renewable sources [33]. Thus, the focus of this research is the expansion of the latter, particularly offshore wind power.

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[a] This chapter contains sections of Dedecca and Hakvoort [1] and Dedecca et al. [21,30] with modifications.

The group including not only the European North Sea but also others such as the Irish or Baltic sea is referred to as the North Seas.

The grid has thus two main functions: to connect offshore wind power plants to onshore systems, and to interconnect these national power systems among them [1]. Traditionally, conventional lines perform these functions separately: they either connect offshore wind farms to the national onshore system, or interconnect two onshore power systems. In contrast, an integrated line performs both functions simultaneously, but no such offshore line existed in Europe by the end of 2017. Integrated lines are

> lines which connect two offshore wind farms or that connect an offshore wind farm directly to an onshore node belonging to another country.

Many studies use this nomenclature, but these lines can also be called hybrid in the literature [25,29,34,35]. Following this definition, Figure 2.1 presents examples of conventional and integrated lines. The integrated grid is defined as

> a grid where the generation and transmission expansion planning considers both conventional and integrated lines, leading to the deployment of the two types.

Therefore, conventional lines can still be a significant component of an integrated offshore grid. Here integrated does not refer to integrated markets (i.e. markets with no transmission congestion), but to the combination of the two grid functions.

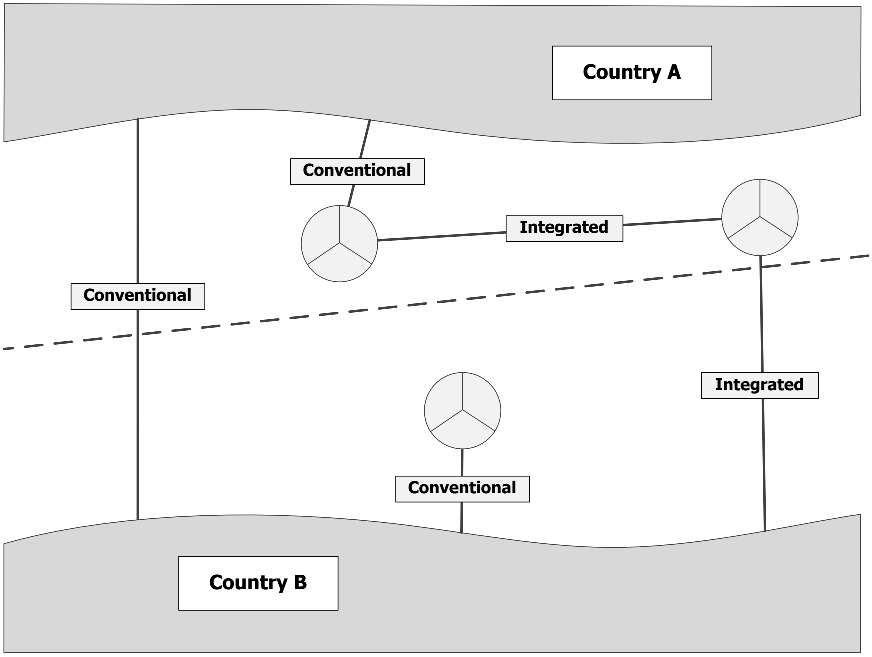

Figure 2.1: Integrated and conventional lines

2.2.1. Characteristics of the North Seas Offshore Grid

The characteristics of the North Seas offshore grid lead to path dependence (section 2.3) and the need of governance for expansion pathways (section 2.4). These 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 2.2. While some of these characteristics are common to all power systems, some are specific to the North Seas grid, as presented in detail next.

Technological	Assets and Projects	System and Actors
Technical Wind intermittency Limited electricity storability Loop flows Transmission interactions	**Asset-related** Lumpiness Asset-specificity Asset durability Capital intensiveness	**Systemness** Economies of scale Dynamic interaction of generation Transmission-generation coordination
HVDC Technology Development required Cost uncertainty	**Project-related** Timing Geography Project timescale Uncertain markets	**Decentralization** Actor multiplicity Internationality Regulatory differences

Figure 2.2: North seas offshore grid characteristics

2.2.1.1. 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 [36]. Since wind marginal costs are low, the variability affects the dispatch merit order (the order on which generation units of different 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 [36]. 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, the ENTSO-E [37] presents a previous review of offshore transmission technologies, while more recent references exist [13,38–40]. Table 2.1 is reproduced from Ergun and van Hertem [39], providing a comparison between power transmission technologies.

Table 2.1: Comparison of power transmission technologies [39]

	HVAC overhead line	**HVAC cable**	**HVAC with power flow control**	**CSC HVDC**	**VSC HVDC**
Power control: active	No	No	Yes	Yes	Yes
Power control: reactive	No	No	Dependent	No	Yes
Grid interconnections	Synchronous	Synchronous	Synchronous	Any	Any
Losses	Low	Low	Low+	Medium	Medium+
Power oscillation damping	No	No	Possible	Limited	Yes
Power reversal	Fast	Fast	Fast	Slow	Fast
Social implications	High	Low	Low	Low	Low
Cost	Low	High	Medium	Medium	High

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. These transmission technologies allow for three types of lines: HVAC, point-to-point HVDC and multiterminal HVDC, as illustrated in Figure 2.3. Specifically, voltage-source converters will be the preferred technology for multiterminal grids with integrated assets, since for longer transmission distances it has investment costs, controllability and integration advantages over both HVAC and current-source HVDC.

However, many aspects of a multiterminal grid are still unproven commercially, especially large DC breakers, control strategies, flow control devices and interoperability between manufacturers. Submarine HVDC transmission technologies (cables, converters and DC breakers) will require innovation to increase maximum transmission capacities, voltage levels and installation depths [37,38,41]. Even though development risks are perceived as low by academia and industry actors [37,42], they still add uncertainty to investment and operation of a future grid. Moreover, if these multiterminal HVDC grids are meshed (i.e. forming loops), power may flow through parallel paths, as in AC systems. This may lead to reduced transmission capacities. Hence, multiterminal lines have both advantages and disadvantages over HVAC and point-to-point HVDC ones.

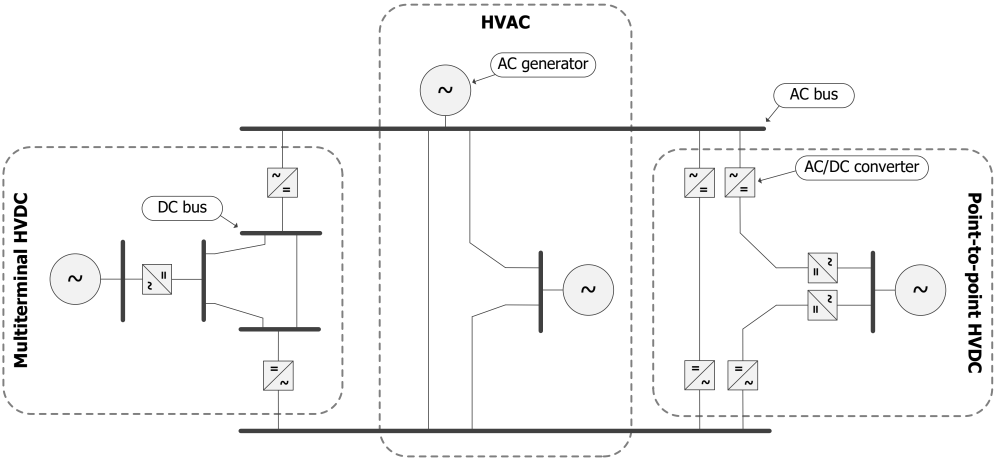

Figure 2.3: Transmission line technologies

2.2.1.2. 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* [3]. Then, the optimal technology and grid topology for an offshore interconnector or wind farm connection depends on *timing, project timescale, geographic disposition and costs* [31,37,43]. 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 is 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 lead time of projects (its implementation duration), for projects of long implementation are riskier and increase the generation-transmission lead-lag issues described below. They would 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.

2.2.1.3. System characteristics: Systemness and decentralization

Systemness is 'the systemic character a sector exhibits' [44]. First, the socio-economic and technical systemness of transmission systems creates *economies of scale,* which do not level out as in generation [3]. Second, transmission and generation projects ideally should be *coordinated but have different timescales*, so transmission expansion can lead or lag generation [45]. Whether lead or lag is prevalent depends on technological and socio-economic aspects. In recent decades transmission expansion is increasingly lagging in Europe [46] 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 the development of onshore generation interact.

Despite this systemness, the concept of the offshore grid is *independent of its technologies and its typologies*, which can range from lesser to greater integration of assets. Indeed, several studies such as De Decker and Kreutzkamp [47], Egerer et al. [48] and Lévêque et al. [49] 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 [50] argues the existing legal framework is sufficient, while Woolley [51] and more recently Gaventa et al. [52] have called for a governance legal framework. On his part, Flynn [53] highlights the *ambiguity of drivers for the grid*. This because support at the European level conflicts with difficulties in regional cooperation and system integration, cost reduction and the national character of financing and offshore wind and transmission development. One can then expect the actual offshore grid to be a combination of conventional and integrated lines.

The next paragraphs cover decentralization, a crucial characteristic class since the offshore grid 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. However, there is no consensus on the necessary level, as the conflicting conclusions of Woolley [51], Meeus [54], Flynn [53], Müller [55] and Piria and Zavolas [56] 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 third-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 (for the connection of multiple wind farms) 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 [54] 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 must 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 offshore wind. 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. [57], EEG [8], or Nieuwenhout and van Hout [58]. It is a core issue for a governance framework for the offshore grid, 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 [59,60] 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 (PCI) is streamlined *permitting procedures*. 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 offshore grid as a complex socio-technical system. Combined with the benefits which the North Seas offshore grid brings, this gives the multiple studies analyzed in chapter 3 their relevance, but also creates comparability challenges.

2.2.2.Benefits of the North Seas offshore grid

The interconnection of power systems leads to benefits in the categories of market integration, climate and the environment, security of supply, European integration, and industrial competitiveness and innovation [9]. Moreover, northern European countries have been developing offshore wind in the last decades for a number of other benefits. While a conventional offshore grid already contributes to those benefit categories, often an integrated grid brings further benefits.

First, concerning market integration, section 2.5 indicates that a conventional or integrated offshore grid leads to a number of economic benefits. The identified welfare gains in the order of tens of billions of euros arise through different but interrelated channels[a]. Through investment savings and further integration of renewables and markets, an integrated offshore grid can even double the welfare gains of a conventional grid. However, results can vary significantly per study, as chapter 3 indicates.

Second, the offshore grid reduces the emission of greenhouse gases, although these are generally already monetized in welfare changes. The ENTSO-E [16] estimates that the CO_2 emission reductions in 2030 from a conventional offshore grid can reach up to 19.5 Mt/y. On its turn, Ciupuliga [61] finds that by 2030 even a conventional offshore grid leads to reductions of 5.0 Mt/y in CO_2 emissions. Also, to the World Energy Council [33] offshore wind in the North Sea can reduce CO_2 emissions by 126.3 Mt/y by 2050. Then, to Cole et al. [31] an integrated offshore grid may reduce CO_2 emissions in the range from 22.0 to 45.3 Mt/y. Generally, studies find that an integrated offshore grid reduces CO_2 emissions more than a conventional one.

Ecofys and RPS [62] indicate that a high development of offshore renewable generation and its associated infrastructure has 'the potential to impact on the wider environment across a range of receptors'. Nonetheless, much of the potential impact 'can be mitigated by sensitive siting and better understanding of the complexities of the receiving environment'. The potential environmental impacts range from the biodiversity to water quality to soil conditions. While there are potential positive impacts, such as for air quality and the marine fauna and flora [62–64], the offshore grid clearly impacts the offshore and onshore environments. In this regard, the integrated offshore grid 'offers the greatest potential to avoid or reduce environmental conflict. This is however subject to sensitive routing and siting of infrastructure, regardless of the final configuration chosen at local level' [62].

Third, the offshore grid increases the security of supply in offshore systems. This by improving the interconnection of European power systems (and their reserves), by reducing the European fuel dependency and bypassing onshore transmission bottlenecks [47,65,66]. Ciupuliga [61] indicates that an optimized integrated configuration is able to maximize the transmission grid utilization while satisfying security standards[b].

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[a] A more efficient dispatch of generating units, the interconnection of renewable resources with a lower availability correlation, the interconnection to flexibility resources such as Scandinavian hydropower, and the reduction of security margins and of transmission losses [9,16,31,47]

[b] However, Ciupuliga [61] does not analyze an N-1 standard, indicating it is not established whether an offshore grid would need such a requirement.

Fourth, the offshore grid is a project with significant political relevance, further contributing to European integration. As indicated in chapter 1, the North Seas offshore grid is a priority corridor for the European Union [17] . It will contribute to the 2030 Climate and Energy Policy framework goals and to the completion of the Internal Energy Market[a] [17,67]. As a consequence, there have been multiple political declarations supporting the development of the offshore grid [25,68,69]. The cooperation of North Seas countries on energy feeds and is strengthened by regional cooperation in other areas, such as the common fisheries policy. An integrated offshore grid requires an increased cooperation of the North Seas countries, thus promoting the European integration further when compared to a conventional one.

Fifth, the offshore grid also contributes to industrial competitiveness and innovation, and European companies are in the forefront of HVDC transmission innovation and deployment [13]. The Strategic Energy Technology Plan [70] and its associated Technology and Innovation Platform on Wind [71] and Smart Networks for Energy Transition [72] promote research and demonstration in various areas. These include new planning methodologies, AC and DC transmission, monitoring, control & interoperability, and market integration & flexibility.

Finally, offshore wind technology itself has a number of advantages. By 2030 the offshore wind economically attractive potential in the European Union (not considering Norway) could reach 780 GW. The technology can supply 25% of the European Union electricity demand at a levelized cost of electricity of 54 €/MWh, or practically all of the European demand for 65 €/MWh [11]. Offshore wind has higher and steadier mean speeds and lower visual impact than its onshore counterpart. Also, the North Seas are shallower than the Atlantic or the Mediterranean, and wind farms can be developed close to large load centers. Moreover, offshore wind may have a positive impact on certain environmental aspects, and turbine capacity is still increasing, as opposed to onshore. On the other hand, despite cost reductions the technology is less established than onshore wind and solar photovoltaic. It is thus more reliant on subsidies, and conflicts with other economic activities are higher than onshore [64,73].

Therefore, the offshore grid contributes not only to addressing the energy trilemma of competitiveness, sustainability and security of supply, but also advances European integration and industrial competitiveness and innovation. Moreover, an integrated grid provides additional benefits when compared to a conventional one. On the other hand, developing an integrated grid requires

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[a] To Sikow-Magny et al. [9] these are 'truly European projects that stimulate and strengthen regional cooperation between Member States' and also with third countries.

technological innovation (as presented in section 2.2.1) and a more complex expansion governance.

2.2.3. Drivers

Specific drivers are enabling the development of the offshore grid, allowing Europe to reap the benefits of the offshore grid indicated above. These drivers are the European Union energy and climate policies, innovations in HVDC technology and in offshore wind generation.

First, due to the 2020 energy and climate targets, renewable energy sources will account at least 34% of the electricity production. Given the potential and the advantages of offshore wind power presented in section 2.2.2, several North Sea countries support offshore wind projects [73]. The European Commission target proposals for 2030 include a minimum share of 32% of renewable sources in European energy consumption [4,6], and the 2050 goals imply the practical decarbonization of the European power sector [73]. According to WindEurope [14] by the end of 2016 Europe had an offshore wind installed capacity of 15.8 GW[a]. Strøm and Grotz [74] indicate firm North Sea countries' commitments will result in at least the installation of 2 GW/year until 2023. The European Union's long-term goals drive the development not only of offshore wind, but also offshore interconnection. Ardelean and Minnebo [13] and Pierri et al. [75] indicate seven interconnector projects to be commissioned in the North Sea in the coming years. Also, the European Union has a target for all countries to reach a minimum of 15% of interconnection by 2030 [9].

Second, as indicated there has been significant innovation in HVDC transmission using voltage-source converters, with improvements in cost, performance, capabilities and maximum power and voltage [38,75]. These transmission systems are already capable of reaching a capacity of 2 GW and a voltage of 500 kV, but the industry will increase those further. The improvement of the technology enables not only further offshore interconnectors, but also the development of multiterminal HVDC grids in the North Seas and Europe in general [75].

Finally, the cooperation of industry, academia and governments has resulted in sharp cost reductions for offshore wind, as reflected in the recent auction prices presented in Figure 2.4 [10]. This interacts with the European energy and climate goals and the HVDC transmission innovations to further develop both offshore generation and transmission, with a positive feedback loop between the commitment of government, industry and developers.

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[a] These were concentrated in the UK (6.8 GW), Germany (5.4 GW), Denmark (1.3 GW), the Netherlands (1.1 GW) and Belgium (0.9 GW)

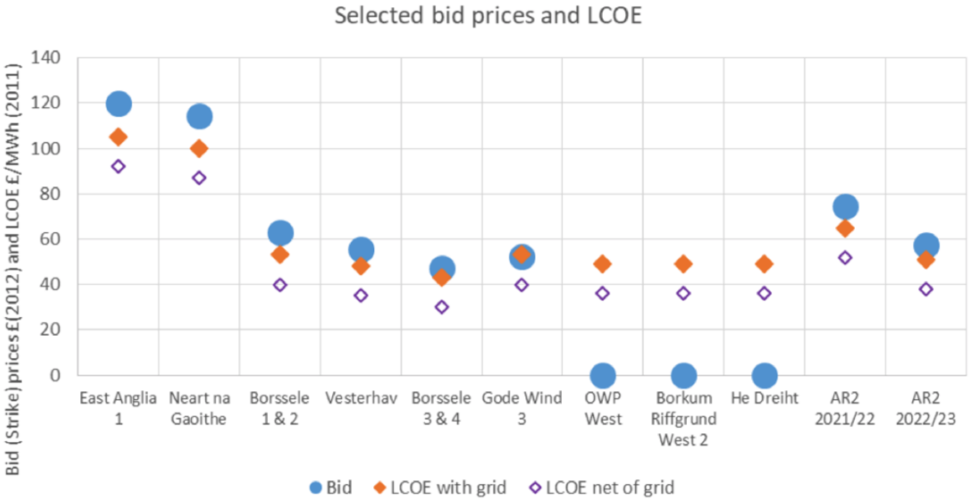

Figure 2.4: Offshore wind auctions and levelized cost of energy [10]

2.3. Governing pathways through system expansion

The offshore grid thus brings significant benefits and has presently important drivers. Since a higher level of integration of the grid functions of connection and interconnection provides greater benefits, the issue arises of how to govern the offshore grid pathway towards more integration.

Given a certain initial state of the offshore grid, a sequence of changes in time lead to a final, different state. A pathway is this sequence of system states, from the initial to the final one. The change of grid assets occurs through investments, and this change determines the expansion pathways, an argumentation that is developed in more detail here.

This thesis is interested in how grids composed of social (actors and institutions) and technical (assets) subsystems change. Actors interact within the social and with the technical subsystem through the investment and the operational management. While the latter comprises the investment in generation and transmission assets and how these are decided upon, the operational one changes the institutions governing the relations among actors and the control of the assets. Hence, the operational management includes but is not limited to the system operation, also comprising the change of the operational rules and contracting between actors. The performance of the system comes not from the individual performance of the subsystems, but from their interaction, which is a determinant feature for infrastructures [44]. In the framework presented in Figure 2.5, the grid is managed by changing its assets and operational control rules.

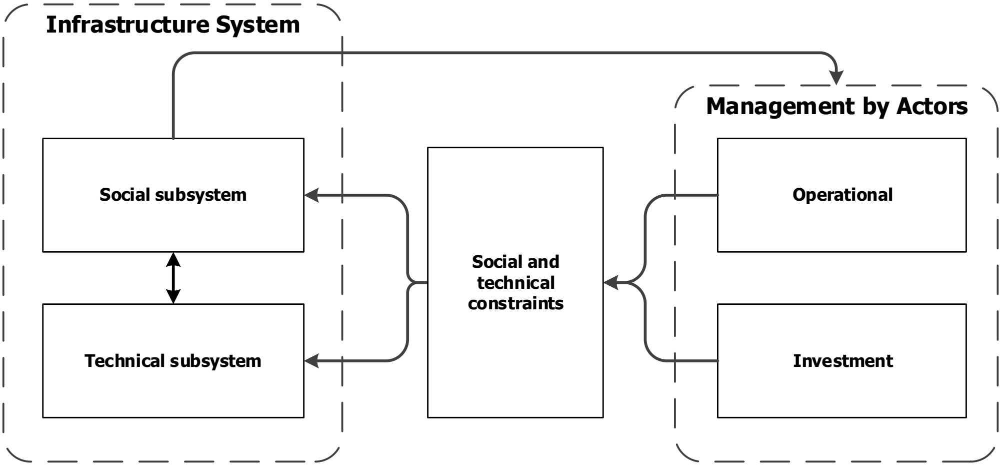

Figure 2.5: Infrastructure change argumentation

However, the characteristics of assets are an important limit to system-level changes, and thus the physical subsystem constrains the possible pathways more than the social subsystem. Namely, changes through investment management are slow since generation and transmission assets are large, capital intensive, durable and specific [44,76]. This also leads to path dependence, where given an initial state reinforcing characteristics lock the system into a certain pathway, in the absence of external influences [77].

In contrast, the operational management for power systems is much less capital intensive than the investment management [78]. For example, in the NorthSeaGrid project, the considered yearly operational costs of offshore HVDC interconnectors do not exceed 2% of investment costs [79]. Even with a low social discount rate of 4% and an asset lifetime of 30 years these costs amount to only 26% of total costs. Confirming this, in its analysis of the characteristics of infrastructures Markard [44] indicates that the capital intensity of the power sector is very high, even when compared to other infrastructures.

Because of the lower capital requirements of operational management and the physical asset characteristics, investments are thus the main determinant constraining infrastructure pathways. Therefore, the importance of the investments to pathways varies but is nonetheless always significant. Section 2.2.1 indicates that the offshore grid shares these asset characteristics of large size, capital intensiveness, asset-specificity and -durability. Therefore, it is also susceptible to inertia and path dependence, with investments defining its pathway. The pathway of the offshore grid is important not only to the investment perspective but also to its operation, since a given grid state (which determines the operation) depends on its pathway.

Investment management to define the offshore grid pathway is not limited only in speed, but also in its extent. Chappin [80] defines transition management as the art of shaping the evolution of socio-technical systems. Similarly, investments can only shape but not determine the offshore grid pathway, due to the asset characteristics, to the decentralization of the grid, to its systemness and to uncertainty.

2.3.1.Expansion planning of power systems

In this way, investments in generation and transmission assets leads to the expansion of the offshore grid. To identify the most beneficial investments, a central process in investment management is expansion planning. Transmission Expansion Planning (TEP) is an important activity for power systems, and Pérez-Arriaga [3] provides a brief introduction to transmission expansion planning while Latorre et al. [81] and Lumbreras et al. [46] review the state of the art. Hemmati et al. [82] review both generation and transmission expansion planning, although the article is similar to Hemmati et al. [83].

Lumbreras et al. [46] indicates five new challenges to transmission expansion planning. The first is the restructuring of the power system, which gives different actors the responsibility for the expansion of transmission and generation, while adding new objectives to the expansion planning activity. The second challenge is the increased penetration of variable renewables in the power system, which are often distant from load centers, thus requiring significant transmission investments for its connection. The third challenge are new large-scale projects aiming at exploiting significant energy resources, but which correspondently require significant investments in long-distance, cross-border transmission. Fourth, the market integration challenge requires that regional transmission expansion planning be jointly conducted by independent actors in a given area. Finally, transmission expansion planning currently faces long permitting processes due to environmental impacts and public resistance.

If expansion planning is challenging, restructured electricity markets and the specific characteristics of the offshore grid make it even more so. The expansion planning of power systems is defined as the process of

> identifying the most adequate investments in generation and transmission to guarantee the future system reliability given certain energy and climate policy objectives. [20]

According to Latorre et al. [81], 'the theory and tools for transmission planning are still below the practical requirements of the new power markets'. Moreover, von Hirschhausen [84] 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 expansion planning methodologies make little use of simulation models, using mainly optimization, heuristics or meta-heuristics to support planning decisions.

2.4. Governance of multi-actor, multi-level systems

Given the importance of investment management to shape the offshore grid expansion pathways, this section discusses which modes the decision-making for this expansion can take. The centralization and decentralization trends of the European power sector are discussed in order to introduce the concept of governance.

Simultaneously with the unbundling of the power sector, the 1st energy package started a process of centralization of planning responsibilities from the national to the European level for the power sector [85]. This was done through top-down measures coupled with bottom-up experimentation and convergence [85–88], and this centralization trend will continue [85,89].

However, there are challenges to the extent and speed of centralization. First, due to uncertainty and the multiplicity of actors, each with different interests and controlling resources relevant to the expansion of European power systems [90,91]. Second, the subsidiarity principle and the national sovereignty on the energy mix establish legal barriers to centralization [85,92]. Third, recently many countries are implementing uncoordinated and diverging measures to guarantee system adequacy given the increased penetration of renewable energy sources (RES). This includes for example various capacity remuneration mechanisms [85,93]. Moreover, a decentralized system has a number of advantages over a centralized one, thus providing an argument against centralization[a].

On the other hand, decentralization also has disadvantages [86]. First, it may be inefficient, with duplicated use of resources in the system. Second, coordination of decentralized and heterogeneous system elements is more complex. Third, decentralized systems may not internalize the externalities inflicted by one system element to another, and are prone to free-riding of actors. Finally, they may be more unstable, since the literature indicates that regulation at the European level is more stable than national ones.

The capacity to govern the offshore expansion pathway is limited both in its speed and extent due to the grid characteristics. Moreover, as seen, investments are central to the expansion pathway, and therefore so are transmission and generation expansion planning. However, the expansion of the European power sector and the offshore grid is a combination of centralization and decentralization in a context of multiple actors acting at various levels. Thus, the concept of

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[a] It allows for technological and regulatory experimentation, does not constrain ambitious frontrunners in their decarbonization policies, is more robust to regulatory design errors, and is more adapted to the heterogeneous contexts and preferences of actors [86].

governance is fundamental for the expansion planning of the offshore grid. Following Bevir [94] governance is defined as

> the combination of heterarchical (non-hierarchical) and possibly hierarchical institutions (formal and informal) that guide decision-making in a networked multi-level, multi-actor system. [21]

2.4.1. Governance forms

Following the definition, it is clear that governance combines different coordination forms. Jessop and Bevir [95] identify four forms: markets, hierarchies, networks, and solidarity (Table 2.2). To the authors, governance by networks

> has a substantive, procedural rationality that is concerned with solving specific coordination problems on the basis of a commitment to a continuing dialogue to establish the grounds for negotiated consent, resource sharing, and concerted action.

Governance by networks is thus fundamentally different from governance by hierarchies or markets. It is also central to the expansion of the offshore grid due to uncertainty and the grid characteristics (especially the multiplicity of actors and levels). In section 2.4.3 the current expansion governance framework of the offshore grid is analyzed, together with the barriers to an integrated expansion.

Table 2.2: Forms of coordination

Form	Definition	Example
Hierarchy	*Ex-ante* coordination through imperative coordination	Firm, organization or state
Market	Coordination through exchange	Day-ahead power market
Network	Ongoing negotiated consent to resolve complex problems in a corporatist order or horizontal networking	North Seas Energy Cooperation
Solidarity	Unconditional commitment to others	Loyalty in small communities

2.4.2. Governance dimensions and theories

As a combination of coordination forms in a complex socio-technical system, governance can be analyzed from different perspectives. Treib et al. [96] develops an extensive categorization of governance separated into policy (instruments), politics (actors) and polity (structure). As an example of an analysis structure for policy, the authors categorize legal instruments for governance according to the implementation obligation (binding or non-binding) and the discretion (rigid or flexible). The authors argue that these are the most crucial dimensions for policy instruments in Europe, allowing the analysis of which instruments political organizations use to reach their goals.

Then, Osofsky and Wiseman [97] discuss the dimensions of governance levels (from national to local) and actors involved (public and/or private). They argue for governance structures involving actors from all types and levels, with a focus on the interstitial regional level to provide flexibility. The dimensions selected also allow them to analyze the interests of actors and the conflicts which emerged in the specific organizations studied (covering regional structures for citizen participation, grid reliability standards, and transmission expansion).

Börzel [98] analyzes the European Union governance through the dimensions of the actors involved and rule structure (hierarchical, or non-hierarchical of mutual influence or adjustment). In this way the author highlights the primacy of public actors and the layered combination of rules structures, characterized as the 'combination of negotiation and competition in the shadow of hierarchy'. Benz [99] also analyzes the European Union governance, but prefers the dimensions of the coupling degree of elements of the governance framework, and of the interaction direction. The author discusses the adequacy of governance modes to provide decision-making flexibility, avoiding lock-ins or vulnerability to strategic behavior.

Finally, Soma et al. [100] study regional governance for an ecosystem based management through the dimensions of integration and cooperation. While integration can vary from being fragmented to coordinated at the regional level, cooperation ranges from the confrontation of economic sectors to them working towards deliberative problem solving. The authors conclude that Europe is moving from a fragmented, confrontational marine regional governance to one that is more coordinated and deliberative. Nonetheless, while they see positive developments in cross-sectoral integration, both dimensions exhibit large gaps.

The examples above apply selected governance dimensions to analyze specific case studies. But there also exist governance theories on how decision making in networked multi-actor, multi-level systems occurs, which apply to multiple case studies. Several authors survey the many governance theories developed to understand multi-level, multi-actors systems [101–103]. By focusing on different dimensions of governance, one can develop specific theories of how this decision-making takes place. For example, multi-level governance focusses the levels [103], collaborative governance highlights the multi-actor aspect [104], and Soma et al. [100] analyzes both levels and marine economic sectors.

2.4.3. Expansion governance of the integrated offshore grid

Thus, specific governance dimensions and theories provide insights into different aspects of decision-making. Before analyzing the future European offshore expansion governance in chapter 6, the current expansion governance framework for the offshore grid is presented.

Some authors analyze the governance of the power sector [88,105–109]. Other works have focused on the integrated offshore grid. For example, the North Seas Countries' Offshore Grid Initiative (NSCOGI) [110] provides guiding principles for the development of an integrated offshore grid. Jay and Toonen [111] indicate how the offshore grid faces barriers and provides opportunities for marine regional governance, while Meeus [54] analyzes different connection models for offshore wind. The PROMOTioN [34] project looks at financial, regulatory and legal aspects for the offshore grid, Müller [112] and Woolley [51] at legal ones, and Delhaute et al. [27] at barriers for both offshore generation and transmission expansion.

Mekonnen et al. [26] separate the governance of future grids into the five building blocks of planning, financing, ownership, pricing and operation. These can also be found in De Clercq et al. [106] and are used in this thesis to organize the offshore expansion governance framework analysis. While financing and ownership are presented here separately, they are tightly related and are frequently analyzed together. Also, the new building block of meta-governance [95] covers the management of the organizations and institutions related to the other building blocks. The current barriers to the North Seas offshore grid can be analyzed according to the expansion governance building blocks of Mekonnen et al. [26], as in Table 2.3.

Addressing these barriers to an integrated expansion of the offshore grid requires actors to cooperate, compatibilize regulation and innovate in all building blocks. Thus, while the integrated offshore grid brings multiple benefits to Europe, a main disadvantage are the resources required to address these barriers.

While a consistent ranking of all these barriers is not available, several authors do indicate main barriers [27–29]. Planning and pricing barriers such as the costs and benefits allocation, the support schemes for offshore wind and the site planning and development of integrated projects are often indicated as significant obstacles to the integrated offshore grid.

Generally, the expansion of generation and transmission will lead to winners and losers among actors. Thus Konstantelos et al. [29] identify 'significant imbalances' in the distribution of benefits among consumers and producers and of investment costs among North Sea countries. To Delhaute et al. [27] 'the distribution of costs and benefits is seen as one of the largest barriers for the development of multi-national assets like interconnectors in meshed structures'.

De Clercq et al. [106] also indicate the distribution of costs and benefits as a major building block to a governance framework, stating that there is still not an agreed-upon redistribution methodology. Moreover, an integrated European site planning and development process is best suited to assess the interaction and impact of multiple transmission lines. However, it may increase the complexity of the planning process and face the resistance of national authorities.

As such, the current European expansion governance framework is reviewed in section 2.4.4 below, which a familiarized reader may skip. This section considers the changes brought by the Energy Union proposals through the Clean Energy for All Europeans package (Clean Energy Package). The adequacy of this framework to enable the integrated expansion of the offshore grid is then analyzed in chapter 6.

Table 2.3: Expansion governance building blocks and barriers

Governance building block	Barriers	References
Meta-governance	Commitment and enforcement	[27,63–65,111–115]
	Innovation and standardization	
	Participation	
Planning	Maritime spatial planning	[27,47,61–63,65,89,114]
	Permitting	
	Site planning and development	
	Onshore connection	
	Priority connection	
	Supply chain	
Financing and ownership	Financing offshore assets	[27,47,54,65,116,117]
	Grid access responsibility	
	Asset legal classification	
Pricing	Support schemes for renewable energy sources	[27–29,54,114]
	Grid connection costs and transmission tariffs	
	Costs and benefits allocation	
Operation	Priority dispatch	[27,38,65,66,118]
	Cost allocation and congestion management	
	Market integration	
	Design parameters of markets	
	Offshore renewable energy sources operation	
	Balancing responsibility of wind farms	
	Other requirements for wind farms	

2.4.4.European expansion governance framework

The current European expansion governance framework results especially from the 3rd Energy Package and the Trans-European Networks for Energy (TEN-E) regulation. The main planning organizations and institutions from the European to the national level are presented in Figure 2.6. The main changes brought by the Clean Energy for All Europeans package (the Clean Energy Package) are discussed in the following subsections [22].

With energy being a shared competence between the European Union and the Member States, the main organizations and institutions are divided between the European, regional and the national level. Dutton [119] presents the evolution of the European power sector until the 3rd Energy Package, separating its analysis between the investment and operation management. The IEA [5] also reviews this structure, adding the changes brought by the TEN-E regulation.

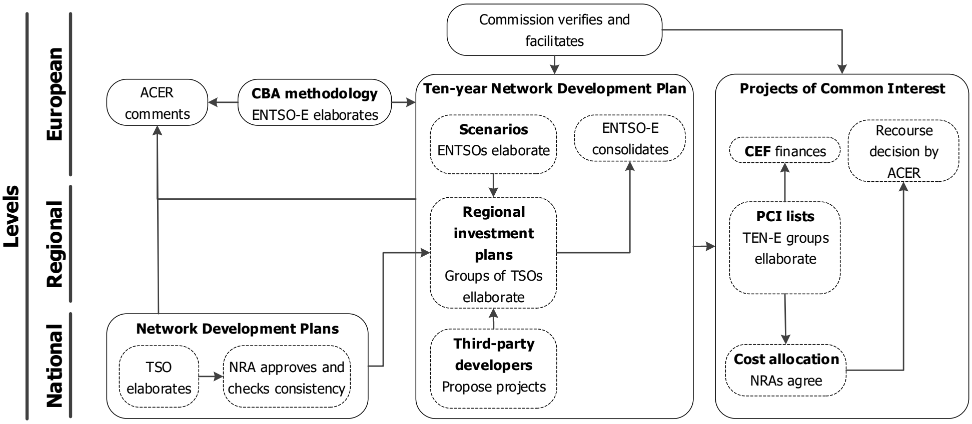

Figure 2.6: European organizations and institutions for expansion planning

The main institutions regarding the expansion planning of the European power system are the national, regional and European investment plans, along with the lists of Projects of Common Interest (PCIs). The 3rd Energy Package obliges transmission system operators (TSOs) to develop an annual network development plan (NDP) with a minimum horizon of ten years, which are then approved by the respective national regulatory authority (NRA). These authorities are also responsible for the coherency of projects in the national plans with the European Ten-Year Network Development Plan (TYNDP). For that, it must consult the Agency for the Cooperation of Energy Regulators (ACER) on any discrepancy.

The ENTSO-E regional groups must develop regional investment plans based on the projects of the National Development Plans and transmission and storage project proposals of third parties. Every regional group must use the common scenarios developed by the ENTSO-E. These regional plans then lead to the biennial TYNDP of the ENTSO-E. Figure 2.7 presents the development process and consultations for the 2016 TYNDP [120]. For 2018 the ENTSO-E cooperated with the European Network of Transmission System Operators for Gas to develop the scenarios [121]. There is thus an interdependency of national, regional and European plans, especially with national projects feeding the regional project lists. The analysis of the costs and benefits of transmission projects at the regional and European levels should follow a methodology developed by the ENTSO-E and commented on by ACER.

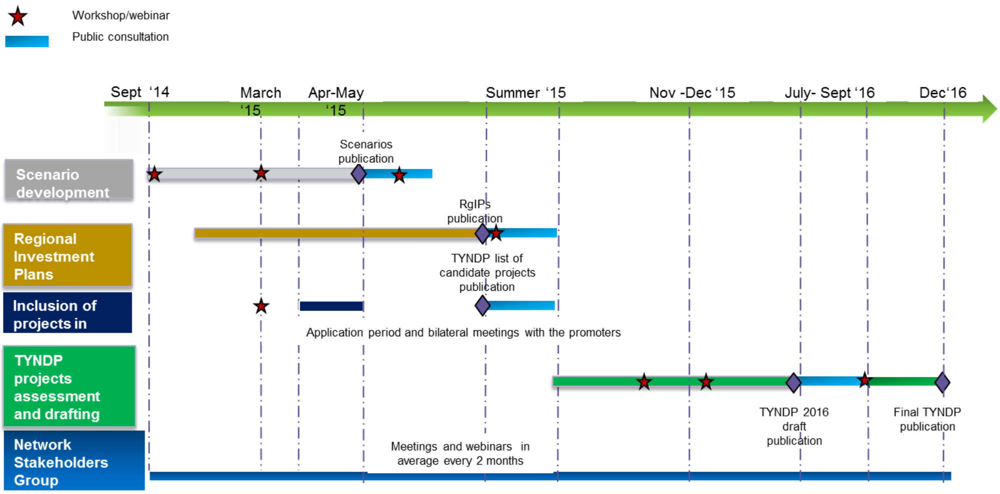

Figure 2.7: 2016 TYNDP process and consultations [120]

In parallel, the TEN-E regulation [17] established the Projects of Common Interest, projects 'necessary to implement energy infrastructure priority corridors and areas'. Each priority area and corridor has a regional group composed of the relevant Member States to develop the project list, with the Northern Seas offshore grid being one of the priority corridors. The PCIs are selected from the TYNDP project list. The groups on their turn are composed of the European Commission, ACER, the ENTSO-E, and regulators, transmission system operators and government representatives of each Member State of the region.

PCIs benefit from improved cross-border implementation and monitoring, simplified permitting, and financing and cost allocation mechanisms [17]. The TEN-E regulation establishes that ACER should monitor the projects' progress and that national regulators should assure they are implemented. The regulation also provides for European coordinators for projects 'encountering significant implementation difficulties'. Member States must also assign one-stop shops for the project permitting process, with a maximum permit granting process duration of three and a half years. Finally, the regulation establishes funding from the Connecting Europe Facility (CEF), cross-border cost allocation agreements between Member States, and economic incentives for high-risk projects. ACER acts as a recourse decision-maker on cost allocation agreements, and the Connecting Europe Facility has a 5.35 B€ budget for 2014-2020 [116].

Responsibilities of the European Commission regarding expansion governance comprise developing new regulation such as the Clean Energy Package and reviewing existing regulation, such as of the TEN-E regulation [122]. Concerning PCIs, the Commission participates in the regional groups, verifies the PCI lists and appoints the European coordinators. Then, it also verifies the final development plan elaborated by the ENTSO-E.

As for ACER, one of its main responsibilities is providing generally non-binding recommendations to official European organizations (the ENTSO-E, national regulators, nominated electricity market operators, and regional operational centres). As such, the Agency for example provides comments on the cost-benefit analysis methodology developed by the ENTSO-E, and on the TYNDP and National Development Plans. It is also a recourse decision-maker (when Member States do not reach an agreement) on PCI cost allocation and on exemptions for merchant interconnectors. Moreover, ACER monitors the PCI list, including its coherency with national plans.

The main changes brought by the 3rd Energy Package were stronger unbundling of transmission system operators, the strengthening of national regulators, the establishment of ACER and of the ENTSO-E, and increasing transparency in retail markets [119]. ACER acts as a coordinator between national regulators, and the ENTSO-E as one between national transmission system operators. The ENTSO-E has other responsibilities, such as covering the development of network codes, ‘coordinated regional network planning’, and developing a methodology for the cost-benefit analysis of transmission projects [123,124].

The energy packages and TEN-E institutions and organizations contributed to the regulation, expansion planning and operation of the European system. They brought benefits such as ‘transparency, interoperability, better monitoring of compliance with EU law, and increased cross-border trading of electricity and gas’ [125]. But despite this, several issues remain. Measures are necessary to address the conflict between the penetration of renewable energy sources and guaranteeing reliability [85,93]. Particularly regarding governance, decision-making is slow with a strong national component, ACER is rather a coordination platform than an actual regulator, and transmission system operators are also restricted in their cooperation [125]. Following an original proposal of Andoura et al. [126], the Energy Union is starting to mobilize actors around these issues and increased energy solidarity in the EU [127,128].

The holistic strategy of the Energy Union aims to integrate the European energy and climate policies to achieve these policies’ targets, focusing on five Energy Union dimensions [7]. The Energy Union proposal as embodied in the Clean Energy Package is still evolving and at the beginning of 2018 was going through the European legislative process. The reception from actors was mixed, with no consensus on many issues. These include binding national targets, European and regional governance, support to renewable energy sources, fair treatment of new flexibility options, and capacity remuneration mechanisms [23,93,129–136].

Arguably, the current Energy Union proposal touches on all aspects of the European energy and climate regulation and policies. However, those more related to the offshore expansion governance are the Union governance, the reform or creation of organizations, the incentives to renewable energy sources, and the design of the internal energy market. Here the main aspects of the Energy Union proposal are presented.

2.4.4.1. Governance of the Energy Union

The Energy Union aims to establish a dynamic, reliable and transparent governance process for the streamlined planning, monitoring and reporting of efforts of Member States. This to ensure 'a coordinated and coherent implementation of the Energy Union Strategy across its five dimensions' to achieve energy and climate targets [4]. This system is necessary given that some energy and climate targets for 2030 are not nationally binding. The need for an Energy Union governance framework was identified also due to the multi-level and multi-actor characteristics of the European energy system and uncertainty [125,137]. Thus, the Energy Union governance framework translates these targets to the national level, relying mostly on a reputational system to guarantee the achievement of the European targets. Ringel and Knodt [138] summarize and analyze the Energy Union governance proposal. It has the potential to become an integrative tool for all Union dimensions [139], and is both novel and pivotal to the Energy Union success [128,140,141].

The main pillar of the Energy Union governance process are the integrated National Energy and Climate Plan (iNECP) and the corresponding progress report. While the national plans compose the planning part of the strategy, the reporting by the Member States allows for monitoring of progress by the European Commission, by other Member States and by stakeholders in general.

iNECPs are decennial, with a (more ambitious) revision possible after 5 years. The Energy Union streamlining objectives were achieved with the integration of fifty different planning, reporting and monitoring obligations into the iNECPs and progress reports. The Clean Energy Package provides templates for the integrated plans with key indicators for each of the Energy Union dimensions. Member States declare their ambitions for each indicator in the plans (developed with parliaments and local and subnational authorities). These undergo then extensive consultations by other Member States and by stakeholders, both for the draft and final versions. Thus, regional cooperation is required in preparing the plans, with Member States exposing any joint or coordinated planning elements and how cooperation was considered. The indicators most relevant to offshore expansion are:

- The use of European support and funding for renewable energy sources
- Specific measures for regional cooperation in renewable energy sources and exportable excess production
- Regional cooperation in energy security and in electricity transmission infrastructure (including the electricity interconnectivity level)
- Steps for streamlined permitting with one-stop shops, information and training

After national plans are defined, Member States report on their progress biennially. The Commission evaluates the national and collective efforts, making formal recommendations for each member state, who must indicate how they have taken the recommendations into consideration (or justify it otherwise). Moreover, in case of insufficient ambition or progress the Commission may levy financial contributions from underperforming Member States to a European financial platform for renewables, and may adjust energy efficiency and renewable energy targets for specific sectors. The Commission may also update the integrated plan and report templates. The result of the monitoring exercise by the Commission is the State of the Energy Union report, sent to the European Parliament and Council. It covers the progress on all targets and indicators as well as on specific energy and climate mechanisms, and the recommendations to Member States.

Due to the importance of the European governance framework, there are several opinions on the shape it should take. Andoura and Vinois [125] are at the origin of the original concept for the Energy Union. Then, Meyer-Ohlendorf [142], Sartor et al. [143] and Turner et al. [144] analyze the governance of energy and climate policies at the European level, while Steinbacher and Schoenefeld [145] and Umpfenbach et al. [146] address the role of the regional level.

Besides these prescriptive studies, other studies have a more analytical approach. Bausch et al. [86] compare the EU emission trading system and renewable energy policies to study the centralization of European energy and climate policies. Fischer [132,141] highlights the evolutionary (as opposed to revolutionary) aspect of the Energy Union, and the importance of the regulatory details. Leal-Arcas and Rios [135] analyze and commend the holistic, cooperative and transparent nature of the Energy Union. Ringel and Knodt [138] and Szulecki [139] focus on the analysis of the governance mechanism of the Energy Union, and finally Talus et al. [147] focus on the renewable energy target and support schemes.

2.4.4.2. Reform of European organizations

Although ACER remains a coordinator of national regulators under the Energy Union and not an European regulator [148], it does receive new responsibilities. First, it is now the recourse decision-maker for cross-border-relevant issues relating to trade, access and operational security. That is, if the national regulators fail to find an agreement or if they opt for ACER's arbitrage, similar to the pre-existing approach to cross-border cost allocation decisions for PCIs. Second, ACER approves the methodology for European resource and short-term adequacy assessment and electricity crisis scenarios. Third, it exerts soft oversight over regional operation centers and nominated electricity market operators, issuing opinions and recommendations. Fourth, it monitors the wholesale market integrity and transparency, one of the most significant and resource-demanding new responsibilities. Fifth, it also monitors the regional cooperation of transmission system operators and of national regulators, although no further details are given on how this should be done. Sixth, the Clean Energy Package requires the periodic review of bidding zones. This review is conducted by the system operators and ACER approves their review methodologies. Seventh, the Agency issues biennial recommendations to national regulators regarding the harmonization of transmission and distribution tariffs. Eight, the Agency defines the methodology for the use of congestion rents for guaranteeing and increasing interconnection capacity. Finally, the decision-making in the Agency's board of regulator changes from two-thirds to a simple majority voting.

ENTSO-E also receives new responsibilities. First, it must create new methodologies for the European resource adequacy assessment, including the value of lost load, cost of new entry, expected energy not served and loss-of-load expectation. Then, it is responsible for the definition of the regions covered by each regional operation center, and in defining a framework for their cooperation.

The Commission has new responsibilities besides the one regarding the governance of the Energy Union. First, it approves a number of proposals, namely regarding bidding zone reviews, the methodology for use of congestion rents and the ACER recommendation for transmission and distribution tariffs convergence. Second, it may request the update of the latter two proposals. Third, it can review the regional groups within ENTSO-E. Fourth, it can add responsibilities not involving decision-making powers to the regional operation centers. Finally, the Commission will be able to adopt network codes and guidelines by delegated acts.

2.4.4.3. Reform of the Internal Electricity Market

As the review of the new responsibilities of European organization shows, the Clean Energy Package brings a number of changes to the design of the European Internal Electricity Market, especially to its operation. The most important change is arguably the creation of the regional operational centers, whose responsibilities go further than of the regional security coordinators, including some decision-making powers. Thus, the centers are responsible for coordinating capacity calculation and reserve sizing, security analysis, common system models, system adequacy forecasts and risk reduction and contingency actions, among others. Of those, the coordinated capacity calculation, reserve capacity sizing, coordinated security analysis and maximum foreign capacity limits for capacity remuneration mechanisms are decisions of the centers, mandatory for transmission system operators [149].

As indicated, the Clean Energy package implements a process for the review of bidding zones. Moreover, the number and divergence of capacity remuneration mechanisms in Europe led to new guidelines, enforcing design principles and cross-border participation. Moreover, the introduction of these mechanisms must be justified by a European resource adequacy assessment. Then, positive price caps in electricity markets are forbidden, while negative price caps must be lower than -2000 €/MWh. Finally, the use of congestion rents is regulated by a guideline developed by ACER and approved by the Commission, and their use to reduce transmission tariffs is forbidden.

2.4.5. Incentives to renewable energy sources

The last main area affected by the Clean Energy Package are the incentives to renewable energy sources. The removal of priority dispatch and the inclusion of balancing responsibility for new large-scale renewable generators is one of the most controversial changes brought by the Package. On the other hand, these generators maintain preferential access (i.e. they are curtailed last) and receive compensation for non-market-based curtailment. Moreover, support mechanisms must be competitive and make renewables market-responsive, with a gradual opening to cross-border participation. Moreover, the Clean Energy Package requires governments to establish one-stop shops for permitting of renewable energy sources, with a manual of procedures and a three-year time limit for the process. Finally, demonstration, small-scale and repowering projects benefit from simplified permitting procedures.

2.5. Conclusions

This chapter presented the integrated North Seas offshore grid, which has technological, implementation and system characteristics – some common to power systems in general, and some specific. *This offshore grid brings benefits regarding the European energy and climate trilemma, European integration, and industrial competitiveness and innovation.* Moreover, the European energy and climate policies, innovation in direct current transmission and sharp cost reductions for offshore wind all drive offshore generation and transmission expansion in the North Seas.

Due to the offshore grid characteristics, *managing offshore investments is pivotal in order to shape expansion pathways towards more integrated ones.* However, 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 offshore grid to certain pathways, without a comprehensive analysis of the possibilities. Moreover, due to the multi-actor and multi-level characteristics *there are limits on the capacity of European actors to shape these expansion pathways,* and even more so for any single decision-maker. *These characteristics and the barriers to an integrated offshore grid make governance both necessary and adequate for offshore expansion pathways.* Any given governance framework is a combination of different coordination forms: mainly hierarchies, markets and networks.

Given the importance of expansion governance for the offshore grid, *the current European expansion governance framework was presented*, with its main organizations and institutions at the European, regional and national level. Also, *a review was conducted of the Energy Union*, the main initiative to reform the European energy and climate governance framework.

The first subordinate research question of this thesis asks how actors in the European power system affect the offshore expansion pathway. The concepts and arguments developed in this chapter indicate that *actors affect the offshore expansion pathway mainly through investments in large, capital-intensive, durable and specific transmission and generation assets.* Moreover, the combination of different governance modes for investment decision-making in offshore transmission and generation is the adequate way to steer towards an integrated offshore grid pathway.

This has a number of implications. First, that *a purely hierarchical mode of governance is inadequate and anyway impossible for the offshore grid*. Second, that *the management of operation is less important than the management of investments for expansion pathways*. Both implications arise from the offshore grid characteristics. This does not mean that hierarchical mechanisms or operation management do not have their place in the offshore grid governance. The former is a significant component of any offshore governance framework, while a reliable and economic operation management of the grid is important not only for its own sake, but also due to its influence on investment management. However, most governance building blocks do not focus on operation. Nor do the identified barriers, of site planning and development of integrated projects, of allocation of costs and benefits, and of the support schemes for offshore wind.

Based on the offshore grid characteristics the following chapters focus on the governance of investments in the integrated offshore grid. A review of energy systems models for the North Seas offshore grid is presented in chapter 3. Then, the Offshore Grid Exploratory Model applies a quantitative modeling approach in chapters 4 and 5 to study these pathways. A qualitative analysis of the offshore grid expansion governance framework under the Energy Union in chapter 6 complements this quantitative approach.

3 North Seas offshore grid modeling[a]

3.1. Introduction

Chapter 2 indicated that the North Seas offshore grid can help Europe to achieve its energy and climate targets, and contribute to European integration and to innovation in many European industries. The chapter also addressed the subordinate research question of how actors in the European power system affect the offshore expansion pathway, highlighting the importance of governance to manage investments in offshore transmission and expansion assets.

The current chapter deals with the second subordinate research question, on which factors affect offshore expansion pathways, as informed by offshore grid models. Quantitative research on the offshore grid can help stakeholders address the governance barriers to it, but there is a plethora of modeling approaches available to study offshore expansion pathways. Therefore, this chapter presents a structured review of the modeling for the North Seas offshore grid. This allows to identify the modeling gaps which the Offshore Grid Exploratory Model will address through the case studies of chapters 4 and 5.

Several research projects in the last years studied the North Seas offshore grid, such as OffshoreGrid, North Sea Transnational Grid or the collaboration between E3G and Imperial College [47,58,150]. Despite these, there is still uncertainty on the offshore grid 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 the relevant but complicated area of energy systems modeling. This chapter first presents a categorization of energy systems models in section 3.2, which also contextualizes the case studies of OGEM of chapters 4 and 5. Then the methodology and results of a review of models for the North Seas offshore grid follow in sections 3.3 and 3.4, respectively.

3.2. Energy systems modeling

For studying energy systems, one can use several methodologies. A first classification can be made between qualitative and quantitative approaches, with modeling composing an important subcategory of quantitative approaches. Energy system models can be classified as top-down or bottom-up as presented in Figure 3.1, adapted from Jägemann et al. [151]. The macroeconomic, sector-aggregated top-down approach opposes the technological, sector-specific bottom-up models.

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[a] This chapter is based on Dedecca and Hakvoort [1] with modifications.

Top-down models consider multiple economic sectors of the system of interest and their interaction. In this way, they are capable of representing feedbacks between those sectors and other phenomena, such as the rebound effect (where increased consumption partly or completely cancels out efficiency gains). However, top-down models do so at the cost of a simplified representation of each sector. Bottom-up modeling on its turn focuses on a specific economic or technological sector. By doing this it represents details of that sector in a manner that would be too complex for top-down models, and thus provides technology-dependent insights into those systems in a way that top-down modeling is unable to, but may not represent feedbacks among sectors [152–154].

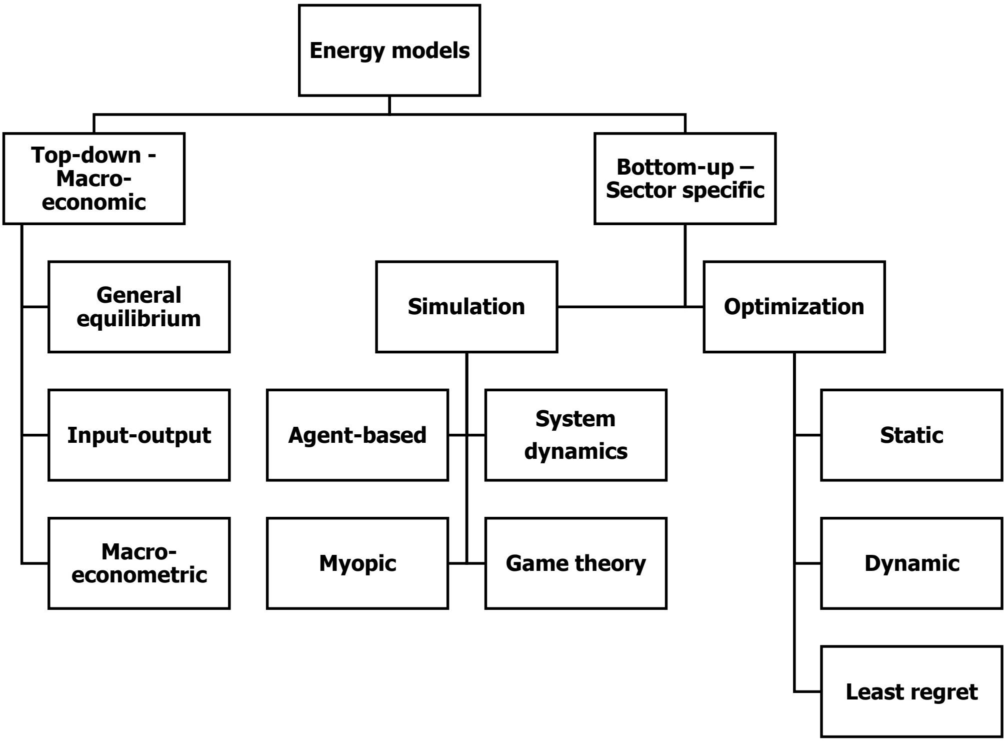

Figure 3.1: Modeling approaches

Bottom-up models can be further sub-divided in optimization and simulation. Simulation models do not strive for optimality, focusing on modeling the decisions of actors or groups of actors [151]. Simulation models have several advantages. First, they allow for the detailed and explicit modeling of complex technical and social system components, and their interaction and timing. Second, a higher number of alternative scenarios can be explored in a context of policy urgency. Third, they surpass human cognition limits, which could not handle such detailed systems. Fourth, system boundaries can be explored to find the most adequate ones, with less *a priori* limitations coming from the modelling approach. Finally, simulation facilitates the analysis of transition management mechanisms [153].

On the other hand, simulation models have drawbacks. First, the application to hypothetical scenarios cannot be compared to the actual development of the energy system, since the latter cannot be fully observed [155]. In addition, the modeling of individual system components must also be validated. This is crucial, since detailed modeling does not imply an adequate representation of reality, e.g. actor decision-making heuristics leading to bounded rationality do not mean necessarily a more accurate representation of reality just because the decision-making heuristics are not optimal [156]. Third, the accuracy of simulations is lesser because of the required modeling assumptions [153]. Finally, transparency is essential as in other modeling approaches, since simulation is not an accurate depiction of reality, but a representation of possible scenarios while simultaneously supporting decisions on relevant and real issues [155].

3.3. Methodology

The review of the offshore grid bottom-up energy models uses a tripartite framework, which is then applied to the analysis. This framework consists of characterizing power systems and the offshore grid, developing categories for the review and then relevant indicators, as indicated in Figure 3.2. The characterization is necessary due to the complexity of the offshore grid, 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 3.2 influence the energy model choice and were discussed in detail in section 2.2.1. In section 3.3.1 the review categories are presented that allow to compare the offshore grid studies, while the indicators are directly presented in section 3.4.

The characteristics of the offshore grid, 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 offshore grid requires considering its characteristics, choosing an adequate model and assumptions according to the research question, and justifying those explicitly.

Van Dam et al. [157] and De Vries [45] 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 in turn 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 presented in the section 2.2 from these socio-economic and technical perspectives.

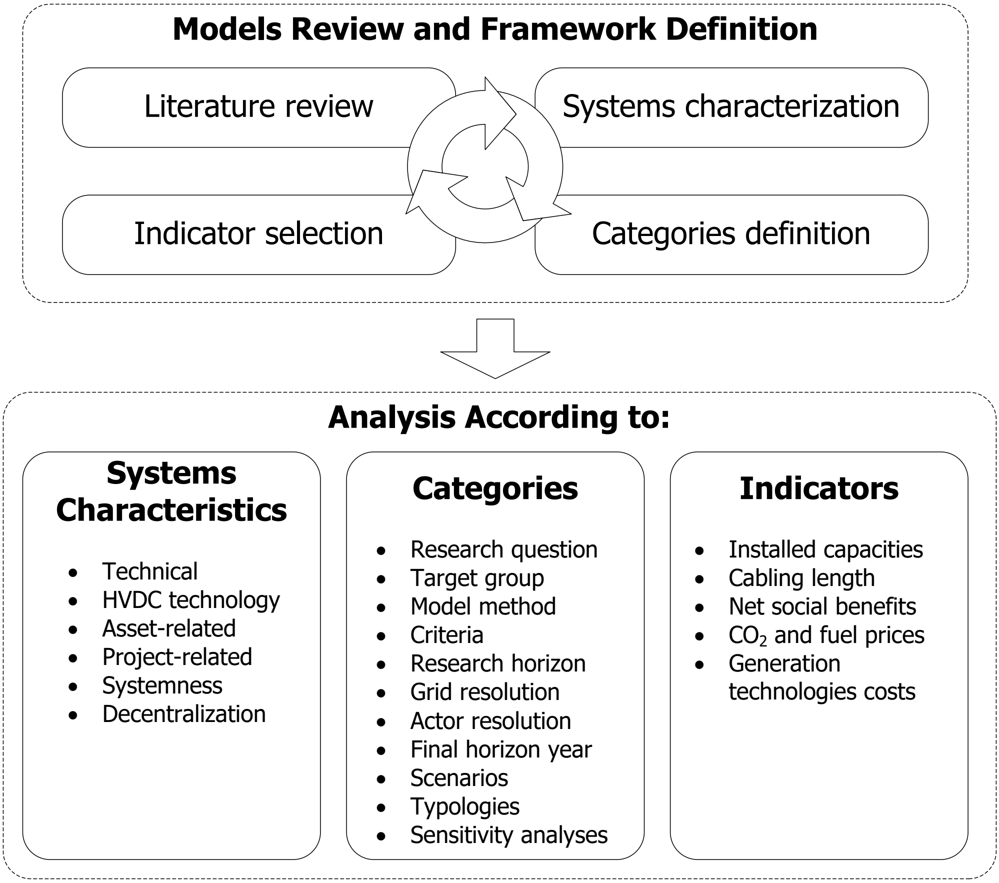

Figure 3.2: North Seas offshore grid review methodology

3.3.1. Categorization framework

This section details the review categorization framework and relates it to the offshore grid characteristics. Connolly et al. [158], Foley et al. [159], Bazmi and Zahedi [160], and Pfenninger et al. [155] provide reviews of energy system models. However, De Decker and Woyte [161] is the only peer-reviewed one dedicated to the offshore grid, 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 offshore grid. Among non-peer reviewed reports, ENTSO-E [162] compares their results to those of NSCOGI [163], while Egerer et al. [164], Haileselassie and Uhlen [66], Pinto [165] and Cole et al. [31] mention or briefly review some existing offshore grid studies. Elahidoost and Tedeschi [166] and Henneaux et al. [167] provide a more recent reviews. The former authors discuss the consequences of offshore grids for transmission expansion planning methodologies, including the need to consider technical aspects and operational capabilities of HVDC systems in topology optimization.

The categories of this review were selected based on own judgment, after considering the energy models reviews mentioned and best practices for the development of wind integration studies from Holttinen [168]. 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 offshore grid 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). However, comprehensive projects can use both horizons, albeit in separate sub-studies.

If all reviewed studies use bottom-up modeling, 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 elements (be they actors, technical components or institutions) and interaction (e.g. existence of an objective function or rules of behavior).

The *criteria* are 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 offshore grid is characterized as geography-dependent and bottom-up modeling 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 level (i.e. consumers, producers and transmission system operators), but present results only at a European or a national level. In this review actor resolution refers to the results presentation, since this is the relevant parameter for readers.

The *final horizon year* and *geographic coverage* are practical choices crucial to answering research questions, considering the path- and geography-dependency of the offshore grid. However, feasibility and input 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 wind power 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 modeling and results, and their differences. Coupled with the system characterization and indicators, they provide a stable reference for this review.

Table 3.1: North Seas offshore grid bottom-up modeling studies

Project	Reference	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. [169]	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 [47]	Investment & Planning		Policy Makers	Optimization	NSB with CO2			Investment	Few nodes	National	2030	1	4	0
	Trötscher and Korpås [170]	Investment & Planning	Operation & Reliability	Scientific Community	Optimization	NSB with CO2			Operation	Few nodes	National	N/A	1	2	3
	Tröster et al. [171]	Investment & Planning		Policy Makers	Optimization	NSB with CO2	RES Int./Curtailment[a]		Investment	Multiple	National	2050	1	1	0
NSCOGI	NSCOGI [163]	Investment & Planning	Operation & Reliability	Policy Makers	Optimization	NSB with CO2			Investment	Few nodes	National	2030	1	2	1
TYNDP 2012	ENTSO-E [172]	Operation & Reliability	Investment & Planning	Policy Makers	Optimization	NSB with CO2	Avoided Emissions	RES Int./Curtailment[a]	Investment	Multiple	National	2020	2	1	1
	Egerer et al. [48,164]	Energy Policy	Operation & Reliability	Scientific Community	Optimization	NSB with CO2	Congestion Revenues		Operation	Multiple	Prod./Cons./Cong.	2020	2	3	0
NSTG	Ciupuliga et al. [173]	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 [61]	Operation & Reliability		Scientific Community	Optimization	NSB with CO2	Reliability	RES Int./Curtailment[a]	Operation	One node	Regional	2030	1	3	1
NSTG WP7	Nieuwenhout and van Hout [58]	Investment & Planning	Energy Policy	Policy Makers	Optimization	NSB with CO2			Investment	One node	Prod./Cons./Cong.	2030	1	3	1
NSTG WP5	Rodrigues et al. [174]	Technology	Operation & Reliability	Scientific Community	Optimization	NSB without CO_2	Power losses	Reliability	Operation	One node	Prod./Cons./Cong.	N/A	1	1	3

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

Project	Reference	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
	Haileselassie and Uhlen [66]	Operation & Reliability		Scientific Community	Optimization	Reliability			Operation	One node	National	N/A	1	1	4
	Drees et al. [175]	Investment & Planning	Operation & Reliability	Scientific Community	Optimization	NSB with CO2	Investment Costs/Benefits		Investment	Multiple	National	2060	1	4	0
	Strbac et al. [150,176]	Investment & Planning	Energy Policy	Policy Makers	Optimization	NSB with CO2			Investment	Few nodes	National	2040	4	5	3
	Cole et al. [31,177]	Energy Policy	Investment & Planning	Policy Makers	Optimization	NSB with CO2	RES Int./Curtailment	Investment Costs/Benefits[a]	Investment	Few nodes	National	2030	3	2	2
TYNDP 2014	ENTSO-E [162]	Investment & Planning	Operation & Reliability	Policy Makers	Optimization	NSB with CO2	Avoided Emissions	RES Int./Curtailment[a]	Investment	Few nodes	National	2030	4	1	0
	Busch et al. [57]	Energy Policy		Policy Makers	Equilibrium	NSB with CO2	Avoided Emissions	Avoided Fuel Imports[a]	Operation	N/A	National	2020	1	1	1
	Buatois et al. [178]	Operation & Reliability		Scientific Community	Optimization	Reliability			Operation	Few nodes	National	2030	3	1	0
SAS	Torbaghan et al. [179]	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. [180]	Investment & Planning	Energy Policy	Scientific Community	Optimization	NSB with CO2	Investment Costs/Benefits		Operation	One node	National	N/A	3	2	0
	Jaehnert et al. [181]	Investment & Planning	Operation & Reliability	Policy Makers	Optimization	NSB with CO2	Investment Costs/Benefits		Investment	Few nodes	National	2030	1	1	1
NSTG	van der Meer et al. [182]	Operation & Reliability		Scientific Community	Optimization	Reliability			Operation	Multiple	National	2025	1	2	2
	Torbaghan et al. [183]	Investment & Planning	Energy Policy	Scientific Community	Optimization	NSB with CO2	Investment Costs/Benefits		Investment	Few nodes	National	2025	1	5	0
	Torbaghan et al. [184]	Energy Policy	Investment & Planning	Policy Makers	Optimization	NSB with CO2	Investment Costs/Benefits		Investment	One node	National	N/A	1	1	2
	Chowdhury and Yanushkevich [185]	Operation & Reliability		Scientific Community	Optimization	Reliability			Operation	Few nodes	National	2030	3	1	0
	Chondrogiannis and Blanco [186]	Operation & Reliability	Energy Policy	Scientific Community	Optimization	Imbalance settlement			Operation	One node	National	N/A	1	1	7

Project	Reference	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
TWENTIES	Farahmand et al. [187]	Operation & Reliability		Policy Makers	Optimization	Investment Costs/Benefits	RES Int./Curtailment		Operation	Multiple nodes per country	Regional	2030	3	3	2
	Torbaghan et al. [188]	Investment & Planning		Policy Makers	Optimization				Investment	Few nodes per country	National	N/A	3	3	0
TYNDP 2016	ENTSO-E [16]	Investment & Planning	Operation & Reliability	Policy Makers	Optimization	Investment Costs/Benefits	RES Int./Curtailment	Avoided Emissions[a]	Investment	Multiple nodes per country	Prod./Cons./Cong.	2030	4	1	0
TWENTIES	Houghton et al. [189]	Energy Policy	Investment & Planning	Policy Makers	Optimization	Avoided Emissions			Operation	1 node per country	Regional	2030	1	4	2
NSON	Kristiansen et al. [190]	Investment & Planning	Operation & Reliability	Policy Makers	Optimization	RES Int./Curtailment			Investment	Few nodes per country	National	2030	4	1	0
	Arregui [191]	Investment & Planning		Policy Makers	Optimization	Investment Costs/Benefits			Investment	Multiple nodes per country	National	2030	4	1	3
NorthSeaGrid	Konstantelos et al. [29]	Investment & Planning	Energy Policy	Policy Makers	Optimization	Investment Costs/Benefits			Investment	Few nodes per country	Prod./Cons./Cong.	2030	1	3	3
	Kristiansen et al. [192]	Energy Policy	Investment & Planning	Policy Makers	Simulation	RES Int./Curtailment	Avoided Emissions		Investment	Few nodes per country	National	2030	1	1	1
	Kristiansen et al. [193]	Investment & Planning		Policy Makers	Optimization	Investment Costs/Benefits			Investment	Few nodes per country	Regional	2035	4	1	0
PROMOTiON	Henneaux et al. [194]	Investment & Planning		Scientific Community	Optimization	Investment Costs/Benefits			Investment	Multiple nodes per country	Regional	2030	8	2	0
NSON and Flex4RES	Traber et al. [195]	Operation & Reliability		Policy Makers	Optimization	Investment Costs/Benefits			Operation	1 node per country	National	2050	1	4	0
	Kristiansen et al. [196]	Investment & Planning		Scientific Community	Simulation	RES Int./Curtailment	Avoided Emissions		Investment	Few nodes per country	National	2030	2	1	0

3.4. Analysis of North Seas offshore grid models

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. The articles up to and including Chondrogiannis and Blanco [186] were originally analyzed in Dedecca and Hakvoort [1] using the full methodology. The remaining articles from Farahmand et al. [187] on were published afterwards and are classified in Table 3.1, but the indicator analysis of section 3.4.2 does not address them. However, the new studies do not alter significantly the conclusions of Dedecca and Hakvoort [1].

3.4.1. Categorization framework analysis

Table 3.1 presents the reviewed studies and their classification according to the categorization framework. For brevity, when categories are related to the offshore grid characteristics they are analyzed only in the characteristics sub-section. Figure 3.3 presents the distribution of the original studies according to some categories of Table 3.1. Already an uneven distribution in the actor resolution and model categories stands out from the data visualization.

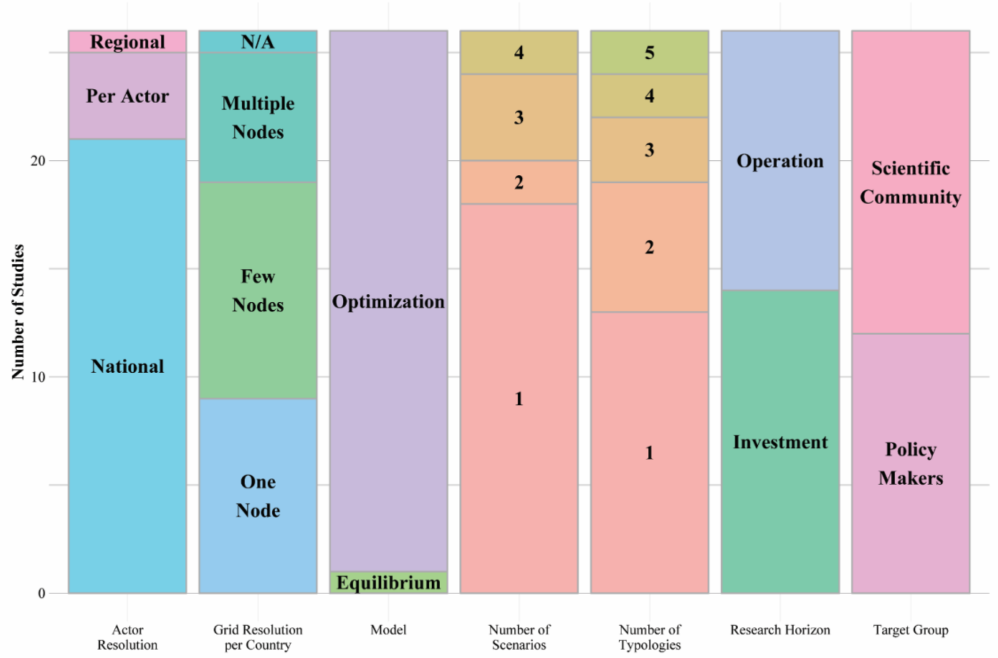

Figure 3.3: Original studies distribution according to categories

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 market demand for these technologies. Therefore, studies of these aspects may use methodologies other than bottom-up modeling. After the original studies, further research projects partly addressed these issues, studying especially flexibility resources, such as Kristiansen et al. [190], or new HVDC technologies, for example Henneaux et al. [194].

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 [53] and Woolley [51]. European and national organizations will directly affect the pathway of the offshore grid 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. [155] 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. [184]. 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 original study uses a simulation model and among the new studies, only Kristiansen et al. [192,196] does. This despite Pfenninger et al. [155] indicating simulation models can contribute to understanding complex systems (of which the offshore grid 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 results of the original studies, 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 so found that welfare is unequally distributed at both levels, and indicate this as a significant barrier to the development of an integrated grid. Nonetheless, the newer studies still overwhelmingly do not analyze net welfare changes and distribution by its components.

The majority of studies looks to the offshore grid 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 horizon under analysis. Regarding the first factor, a more integrated offshore grid will only be possible closer to 2030, or even later. Thus 2020 can be currently considered too restrictive, while offshore grid studies for 2040 or later are interesting, especially considering the 2050 European goals. Of the newer studies, Kristiansen et al. [193] and Traber et al. [195] are the exception, looking into 2035 and 2050 respectively. 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, offshore grid 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 modeling limitations, while the same can be stated for 2020 regarding earlier studies. However, this horizon may improve with the publication of the 2018 TYNDP looking into 2040 [197].

3.4.2. 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, among the original studies. 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 3.4 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 third-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) offshore wind power capacities range from 30 to 150 GW, with an average of 86 GW. As a comparison, EWEA [198] in its scenarios considers a total capacity from 19.5 to 27.7 GW in 2020.

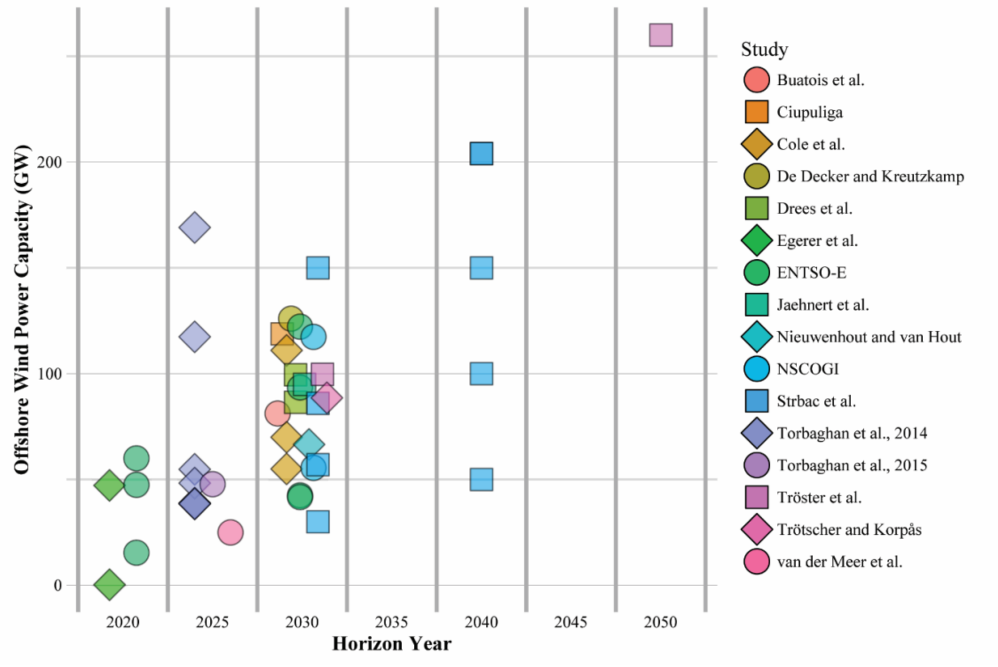

Figure 3.4: Offshore wind power installed capacities

Figure 3.5 presents the *cabling lengths and offshore wind power 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 [47] and ENTSO-E [172].

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 affect 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 laying, a benefit of a meshed offshore grid mentioned in studies. For example, all meshed typologies from Cole et al. [31] have less cables for the same wind power capacity, but the inverse is true for De Decker and Kreutzkamp [47].

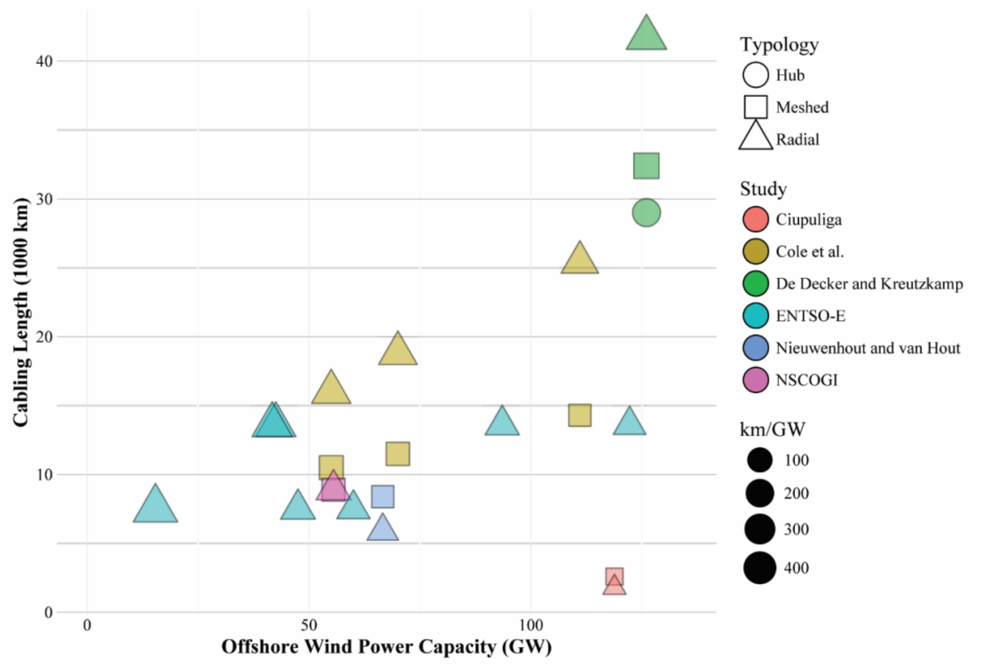

Figure 3.5: Cabling lengths and offshore wind power capacities

Figure 3.6 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 net social benefits 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, these 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 are a main argument for the coordination of its development and the sharing of interconnection and connection. Besides the studies that provide a total net social benefits value, a few others provide an annualized value. Both types indicate that an integrated grid is more beneficial than a less integrated one, at a European level. The exception is Torbaghan et al. [179], 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 benefits 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 offshore grid. 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.

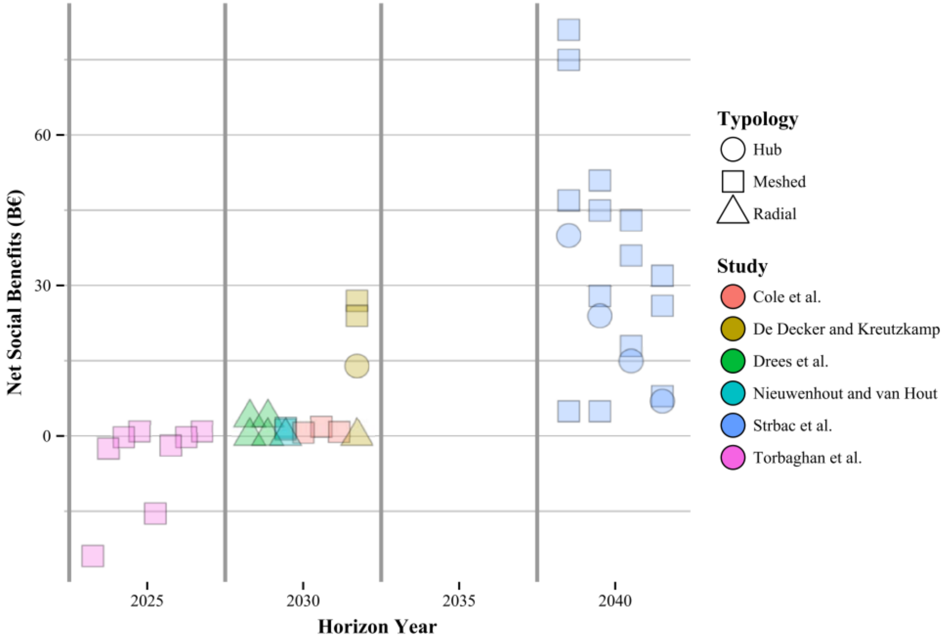

Figure 3.6: Net social benefits of offshore grid studies

Figure 3.7 presents the available *CO_2 prices and fuel and electricity generation costs*, also indicated in Table 3.2. 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.

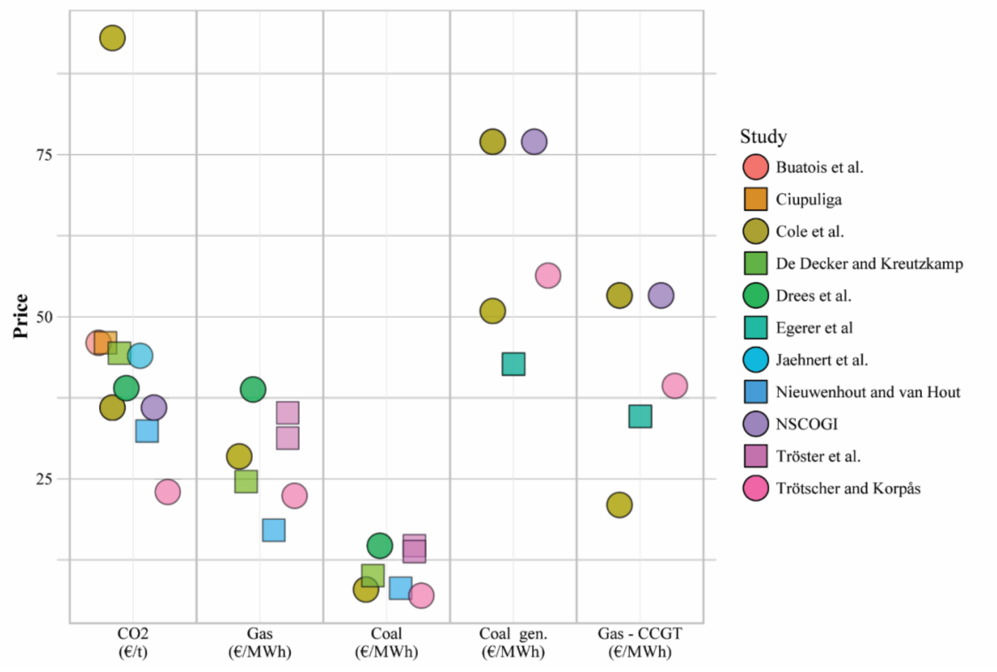

Figure 3.7: CO2 and fuel prices, and electricity generation costs

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. [31] 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 (exogenous) CO_2 and fuel prices and net benefits indicate no consistent pattern between higher prices and higher net benefits. For instance, Drees et al. [175], NSCOGI [163] and Cole et al. [31] have the highest fuel prices, but not the highest net benefits – even considering only operational net benefits, those of Strbac et al. [150] are much higher.

Other factors that influence results include forecasted demand, intertemporal modeling 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.

Table 3.2: 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. [178]	Single	2030	46.0				
Ciupuliga [61]	Reference	2030	46.0				
Cole et al. [31,177]	Scenario 1	2030	93.0	28.5	8.0	50.9[a]	21.0[a]
Cole et al. [31,177]	Scenario 2	2030	36.0			77.0	53.3
Cole et al. [31,177]	Scenario 3	2030	36.0			77.0	53.3
Cole et al. [31,177]	Fuel Sensitivity	2030	93.0			77.0	53.3
Cole et al. [31,177]	CO2 Sensitivity	2030	36.0	28.5	8.0	50.9[a]	21.0[a]
De Decker and Kreutzkamp [47]	Single	2030	44.4	24.6	10.1		
Drees et al. [175]	EWI A	2030	39.0	38.8	14.7		
Drees et al. [175]	EWI B	2030	39.0	38.8	14.7		
Egerer et al. [48,164]	2009	2020				42.7	34.7
Egerer et al. [48,164]	Wind+	2020				42.7	34.7
Jaehnert et al. [181]	Single	2030	44.0				
Nieuwenhout and van Hout [58]	Reference	2030	32.4	17.1	8.2		
NSCOGI [163]	RES+	2030	36.0			77.0	53.3
NSCOGI [163]	Reference	2030	36.0			77.0	53.3
Tröster et al. [171]	Scenario A	2050		35.2	14.7		
Tröster et al. [171]	Scenario A 2030	2030		31.3	13.8		
Trötscher and Korpås [170]	TradeWind	2030	23.0	22.4	7.0	56.4	39.4

3.4.3. North Seas offshore grid 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 2.2.1. 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

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[a] Does not include the CO_2 costs

wind capacity of Figure 3.4. 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 on 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 offshore grid, 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 offshore wind generation. As for *hydropower generation and storage*, there are three main approaches. These are ignoring intertemporal constraints, using a two-tiered model, or using a maximum annual energy availability. Modeling 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. [199]. Thus, generic statements such as 'increased interconnection capacity always benefits consumers of importer countries' usually do not apply directly.

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. [57] 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* are presented separately and usually not valuated, such as the environmental impact of cabling & landfall installations and the effects on existing merchant interconnectors. 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 by eliminating congestion rents.

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 [61] 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 offshore grid actors. These characteristics impose therefore their own specific requirements on modelers, who need to justify their choices accordingly.

The main offshore grid *technological issues* are costs and voltage-source multiterminal grids development considering control strategies, standardization (affecting vendor interoperability) 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. [171]. Nieuwenhout and van Hout [58] do realize a survey of offshore transmission costs. Trötscher and Korpås [170] in their turn 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 voltage-source HVDC control strategies, such as Haileselassie and Uhlen [66] or Rodrigues et al. [174]. 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. Recently, Henneaux et al. [194] addressed this by analyzing the commercial availability and cost of these circuit breakers, and Härtel et al. [200] reviewed cost parameters for VSC HVDC.

Offshore grid typologies are exhaustively treated with optimization models in all horizons and for the main research questions, as Table 3.1 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 [61] and Tröster et al. [171,171].

Approaches to treat the *geography dependency* include portfolio analysis to determine wind farms suitable to hub connection, e.g. De Decker and Kreutzkamp [47], detailed heuristics for the optimum connection typology for identified wind farms, e.g. Cole et al. [31], and complementary abstract cases studies. However, the use of studies from third parties and aggregation of offshore wind 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) modeling 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 (considering the interrelation of expansion periods) is a gap in offshore grid research which prevents modeling timing dependency. Pfenninger et al. [155]

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

Regarding *endogenous modeling of regulation*, Torbaghan et al. [179,184] do model capacity and energy support schemes for offshore wind, and Busch et al. [57] analyze different cost allocation schemes. However, there is a need for further endogenous modeling of regulation in bottom-up studies of the offshore grid. This results from the range of regulatory tools available, and the importance for the integrated offshore grid of energy policy in Europe and of policy makers as a target group.

3.4.4. 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 [84] on supergrids. The author notes '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[a]. 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 [150]. Additionally, newer studies looking at the allocation of costs and benefits such as Konstantelos et al. [29] and Kristiansen et al. [196] elucidate the impact of this allocation and the principles it should follow.

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 [201] can provide interesting results and be feasible for offshore grid 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. Also wind capacities in other Northern seas such as the Baltic can be up to 40% of total capacity [47,202]. Therefore, the inclusion of all northern seas is an important consideration. Recently, the Baltic InteGrid project [203] began analyzing in detail the development of an integrated offshore grid in that region.

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[a] Such as the distribution of benefits and costs between countries and actors, technology costs, support mechanisms, and expansion planning coordination.

Future technical developments that can impact the offshore grid 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 [150,180]. There is ample space for future research to study these under broader assumptions and different modeling approaches, for example as done by Kristiansen et al. [196].

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

3.5. Conclusions

This chapter reviews the North Seas offshore grid modeling studies according to a categorization framework, the characteristics of the offshore grid, selected indicators and other considerations. While the analysis is more extensive for the original studies covered by Dedecca et al. [1], several additional studies are categorized in Table 3.1. The new studies do not alter the main conclusions of this review significantly, although there are advances. These regard the consideration of future energy technologies, the distribution of costs and benefits among countries and actors, and the endogenous modeling of regulatory mechanisms such as support schemes for renewable energy sources.

Despite these advances, this *review does establish that the endogenous consideration of regulatory mechanisms and of the distribution of costs and benefits is rather the exception.* Moreover, *bottom-up models employ predominantly optimization over simulation approaches. Using an alternative modeling approach to study the offshore grid provides different insights than an optimization approach.* Also, simulation can simultaneously support the endogenous consideration of regulation and the distribution of costs and benefits, thanks to its greater freedom in modeling system characteristics.

The review of the existing offshore grid models and the consideration of alternative bottom-up modeling approaches addresses the second subordinate research question: which factors affect offshore expansion pathways as informed by offshore grid models? *The combination of approaches provides complementary normative and exploratory expansion pathways. These highlight a number of investment management factors*, especially when the costs and benefits distribution and governance barriers are considered. The reviewed models allow the comparison of normative conventional and integrated pathways which indicate the latter increase social welfare, but there are still modeling gaps to study the integrated offshore grid.

Therefore, in this research *the Offshore Grid Exploratory Model (OGEM) was developed. OGEM employs simulation exactly to address these aspects.* In chapter 4 a simple offshore grid is modelled in order to study transmission expansion pathways. Then, chapter 5 develops a more detailed case study of the North Seas offshore grid covering both transmission and generation expansion.

At the same time, *the modeling review presented in this chapter also evidences the limitations of quantitative approaches in general.* Thus, qualitative approaches can complement quantitative ones by having even greater freedom in considering regulatory and welfare distribution aspects. Thus chapter 6 leverages a qualitative approach to study regional governance for the offshore grid, complementing the quantitative analyses of OGEM.

4 Offshore transmission expansion pathways[a]

4.1. Introduction

The review of the North Seas offshore grid models of chapter 3 indicates that the use of different modeling approaches provides complementary insights into this offshore grid. Nonetheless, most models leverage classic optimization, with very few applying simulation approaches. Section 3.2 also indicates that simulation models can represent system components with a high-level of detail and without *a priori* limitations on the system boundary. They also make exploratory studies possible, facilitating the analysis of transition management mechanisms [153]. Therefore, simulation models on the offshore grid allow the exploration of transmission expansion pathways, simultaneously filling a modeling gap.

The third subordinate research question asks how governance barriers affect expansion pathways towards an integrated offshore grid. The Offshore Grid Exploratory Model is thus a simulation model developed in this thesis to explore the expansion pathways of the North Seas offshore grid. It analyzes the influence of governance barriers and several factors affecting these pathways in two case studies presented in chapters 4 and 5. On the one hand, chapter 4 studies transmission expansion pathways with a conceptual case study of an offshore grid on the North Sea, focusing on path dependence and the investment management factors. On the other hand, chapter 5 develops a transmission and generation expansion pathways with a detailed case study of the North Sea. It uses data of the e-Highway2050 [87] project, focusing on governance barriers to generation and transmission expansion.

Section 4.2 introduces the modeling approach of OGEM (myopic optimization) and the governance constraints used to model governance barriers in OGEM. Then, section 4.3 presents the OGEM model and data used in this chapter to conduct a conceptual case study of offshore transmission expansion pathways. Finally, section 4.4 presents the case study results, and section 4.5 concludes on the investment management factors, drawing principles for offshore expansion planning.

4.2. Exploration of the North Seas offshore grid pathways

A particular approach to simulation is myopic optimization (also called shortsighted), where the optimization horizon considers only part of the whole problem (e.g. a limited area or time period). In this way myopic models do not guarantee global optima as perfect foresight optimization does, and can be classified as simulation models.

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[a] This chapter is based on Dedecca et al. [21] with modifications.

The simulation approach of OGEM leverages the advantages of simulation models: exploration of scenarios with detailed and explicit details, with flexibility on system boundaries and flexible analysis of transition management mechanisms such as investments. On the other hand, OGEM addresses the disadvantages of simulation models. This through verification and validation, open publication of model and data, and the exploratory rather than prescriptive analysis of expansion pathways.

In OGEM the expansion pathway for the offshore grid is composed of sequential period expansions as in Figure 4.1, and thus the approach is myopic because each optimization considers only the current period. Hence, OGEM is a sequential static model following Lumbreras et al. [46]. OGEM complements the perfect-foresight and robust optimization approaches of current offshore grid models. It does so by providing non-optimal and path-dependent expansion pathways which realistically represent decision-making by considering governance constraints and path dependence.

On the other hand, this approach does forfeit the benefits of dynamic generation and transmission expansion planning. Considering the inter-period interaction of the generation and transmission would lead to different expansion pathways with higher benefits [204,205]. The myopic approach is chosen to complement existing expansion models on the offshore grid, for computational tractability, and for an exploratory rather than prescriptive approach.

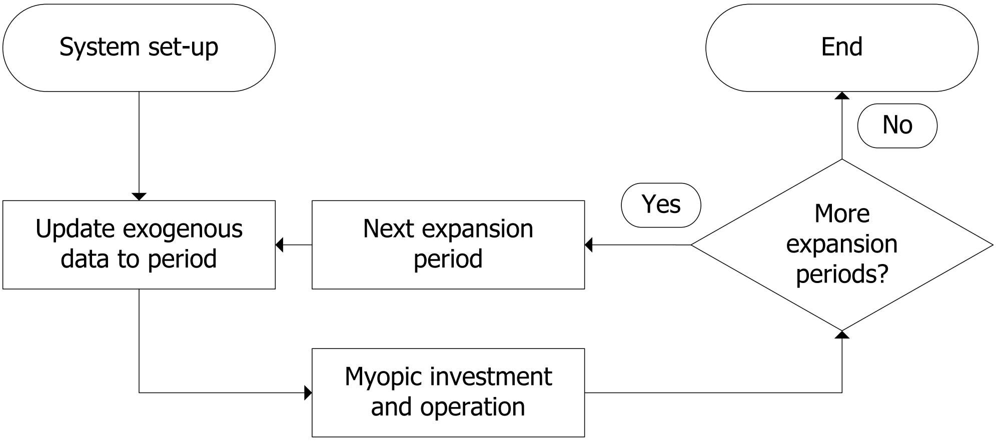

Figure 4.1: Myopic OGEM sequential investment and operation

While OGEM employs myopic optimization in both chapters 4 and 5, it applies different optimization approaches. On one hand, in chapter 4 OGEM uses classic optimization for the economic dispatch of the system (optimizing its operation), while using optimization heuristics to define the transmission expansion pathways (i.e. the investment in transmission assets). On the other hand, chapter 5 OGEM uses classic optimization both for the investment and economic dispatch of the system.

4.2.1. Governance constraints

Section 2.4.3 indicates that planning and pricing barriers such as the costs and benefits allocation and the integrated site planning and development are significant barriers to the integrated offshore grid. OGEM models these barriers through the governance constraints. Governance constraints as listed in Table 4.1 are introduced here, while their actual implementation varies and is detailed in chapters 4 and 5.

The first governance class of OGEM are welfare constraints. Welfare constraints represent the interests and resources of each North Seas country. Each country has an interest in developing integrated lines only if these increase their welfare, and can block generation and transmission expansions in their territory if so desired. Welfare constraints can be Pareto or Kaldor-Hicks constraints. The Pareto constraint requires that the net welfare of each and every country participating in an expansion increases. The Kaldor-Hicks constraint in its turn requires only that the combined net welfare of all participating countries increases, which *theoretically* allows the coalition to compensate any countries which suffer net welfare losses.

The second governance constraint class are integration constraints. These constraints limit the number of integrated projects that can be built at any single expansion period. The integration limit ranges from unconstrained (there being therefore no planning barrier) to not allowing any integrated expansion. In the latter case planning barriers such as difficulties in integrated maritime spatial planning or site planning and development are so high they do not permit any integrated project to be developed at all. This represents integration constraints as affecting the possibility of investing in integrated projects, while an interesting alternative could be to use higher investment costs for these, representing the costs of efforts such as of planning and coordination.

Table 4.1: Governance constraints

Constraint class	**Governance constraint**	**Description**
Welfare	Pareto	Increasing welfare for every participating country[a]
	Kaldor-Hicks	Increasing welfare for coalition of participating countries
Integration	Unconstrained[b]	No limit on integrated lines built per period
	Complex integration	One integrated line built per period per node
	Disintegrated planning	No integrated lines allowed

4.3. OGEM for transmission expansion

Chapter 3 demonstrates that transmission expansion planning commonly uses perfect foresight optimization approaches. Moreover, section 4.2 indicates simulation is an adequate alternative to model transmission expansion pathways of offshore grids which change through investment. For this, the model simulates sequential investment periods forming an expansion pathway, with three steps per period: creation of an expansion portfolio, operation of the system, and investment management of expansions. This is indicated in Figure 4.2, which details the general flow of Figure 4.1 and follows the operational and investment dichotomy presented in section 2.3.

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[a] Following the economics definition for Pareto improvements, the net welfare should be non-decreasing for every country while improving for at least one. Due to numerical modelling considerations they are here required to at least marginally increase for every country, without impacting the simulation results.

[b] Referred as social scope in Dedecca et al. [21].

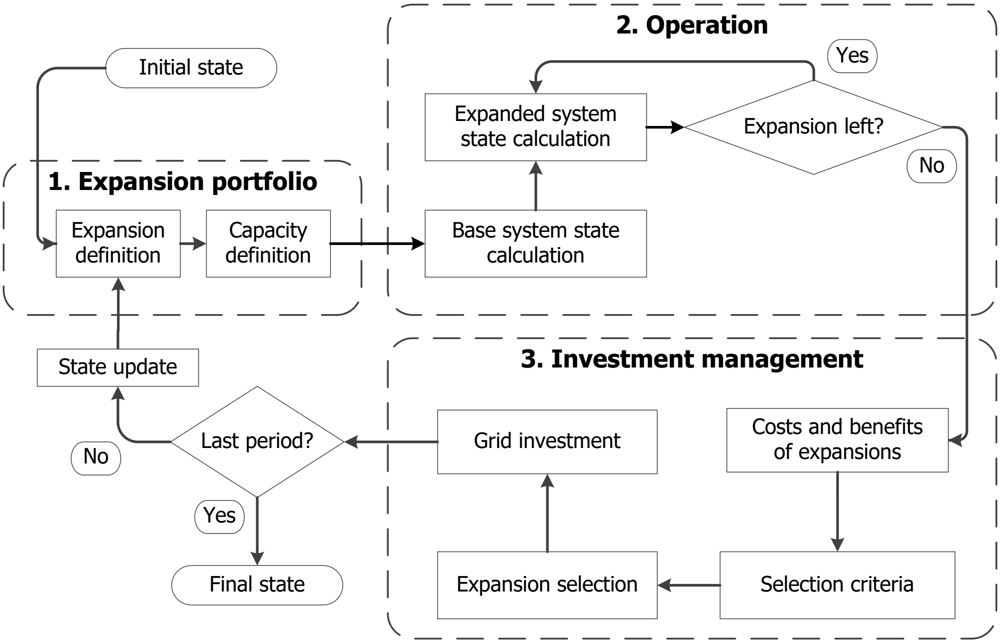

Figure 4.2: The offshore grid simulation model

The first step develops the portfolio of expansion candidates, defining the expansions of the system to be considered in the current period, with each expansion belonging to one of six possible typologies. Typologies are grid archetypes defining allowed interconnectors and wind farm connectors, in paths that are conventional or integrated. Conventional paths are the shortest path to an onshore node, while integrated paths pass through offshore hubs or wind farms. On their turn, expansions are specific grid realizations belonging to a typology and combining the allowed lines in different ways, so that multiple expansions exist for each typology.

As an example, Figure 4.3 presents two expansions belonging to the radial split typology. The example expansions combine in different ways: a split interconnector passing through one single wind farm; a conventional connector for a wind farm; and a conventional interconnector. Figure 4.5 indicates the allowed lines that define each typology, which are discussed in detail in section 4.3.2.

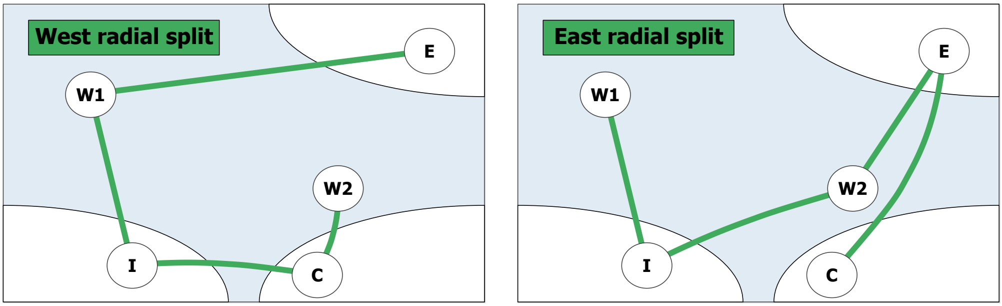

Figure 4.3: Example of expansions of the radial split typology

In the following step of system operation (section 4.3.4), the system state for the base case and for each expansion is calculated individually, by finding the optimal power flow which minimizes the generation operational costs of the system. Each considered expansion may reduce these costs in relation to the period base case.

Finally, the investment management step (section 4.3.3) calculates a comparative cost and benefit indicator for each expansion, using the present value of net benefits from the base system to the expanded system. The net benefit is composed of the increase in welfare minus transmission investment costs. Then, the expansion of the portfolio with the highest cost and benefit indicator is selected and invested in, and the three simulation steps are iterated until the final period is reached.

4.3.1. System representation

The model nodes represent offshore wind farms, offshore hubs, and onshore power systems. In each period onshore nodes are categorized as exporter, importers or common nodes, according to their base system nodal price (respectively low, high or intermediate). Offshore hubs are nodes which do not generate or consume any power, serving only as connection points.

The expansion pathways are split into periods, and each period is composed of multiple non-sequential snapshots (Figure 4.4). While periods represent the sequential expansions of the offshore grid, snapshots represent a year of operation of the power system by aggregating the hours of the year. A snapshot represents a number of hours of the year with a certain availability of renewable resources such as solar radiation and wind. Thus, the generation capacities vary between periods, while the resource availability for each renewable energy technology varies by snapshot. Hence, the total system performance for an operational year is given by the weighed sum of the snapshots, with the weights being the number of hours they represent. In this study demand is inelastic and constant in all periods. In its guideline for the cost-benefit analysis of transmission projects the ENTSO-E [206] uses the term of planning case to refer to snapshots.

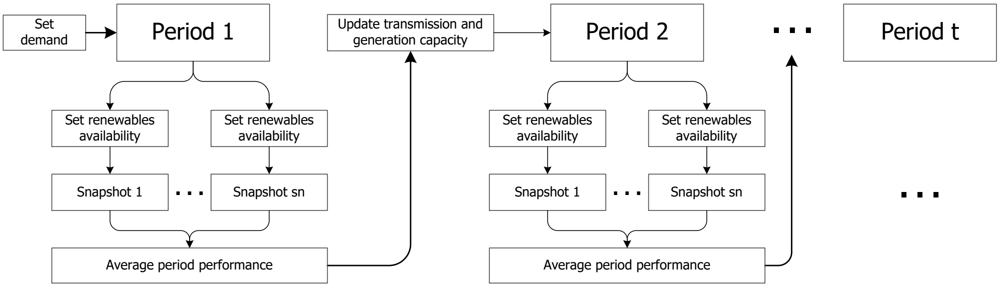

Figure 4.4: Simulation hierarchy of periods and snapshots

4.3.2. Expansion portfolio

The transmission line types considered are those presented in section 2.2: HVAC, point-to-point HVDC and multiterminal HVDC. There are six typologies as indicated in Table 4.2. Figure 4.5 presents one possible realization of each typology, with the allowed connectors and interconnectors. First, in the hub typology one offshore hub concentrates all interconnectors and connectors, which are thus integrated. Second, the radial typology has only conventional interconnectors and connectors. Third, in the farm-to-farm typology onshore nodes are interconnected in an integrated manner, passing through both wind farms. Fourth, the split typology is characterized by only integrated interconnectors, passing through a single wind farm each. Fifth, the IC split typology is a mixed typology which combines an integrated split interconnector with a conventional interconnector. Finally, the radial split typology adds to the IC split typology a conventional connection of the remaining wind farm.

Table 4.2: Transmission typologies

Typology	Color	Description
Hub	🟪	Only integrated interconnectors and connectors to an offshore hub
Radial	🟥	Only conventional interconnectors and connectors
Farm-to-farm	🟫	One integrated interconnector passing through two wind farms
Split	🟦	Only integrated interconnectors, each pair passing through a single wind farm
IC split	🟧	Combination of integrated split and conventional interconnectors
Radial split	🟩	Combination of integrated split and conventional interconnectors with a conventional connector

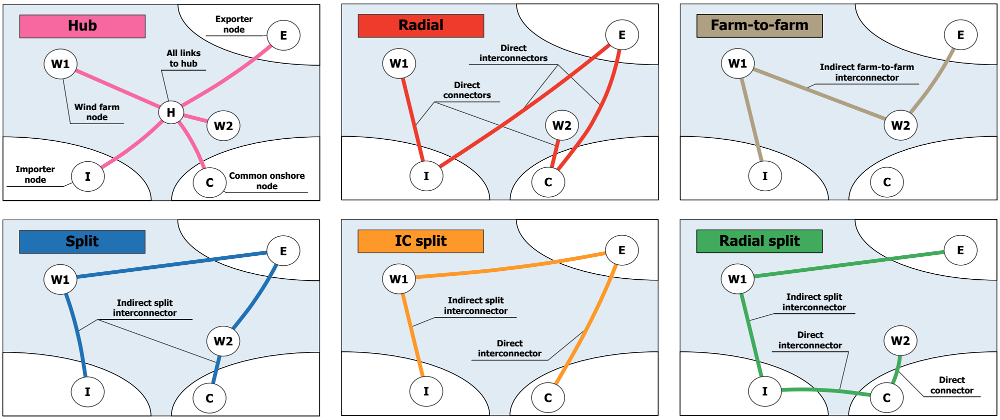

Figure 4.5: Transmission typologies

As section 4.3 indicates, for each of these typologies there are multiple possible expansions, each with specific combinations of the allowed lines. Section 4.4.3 identifies factors which influence expansion pathways, among which are typology characteristics. Typology characteristics affect investment costs and line congestion, comprising the factors of grid function integration (trading-off cable investment costs and congestion) and of level of terminal capacities (trading-off terminal investment costs and congestion of cables). However, modeling and simulation factors also influence expansion pathways. Therefore, some factors are not typology-specific, and thus expansions belonging to the same typology affect expansion pathways differently, through the modeling and simulation factors. Another interesting possibility to study would be several smaller, disconnected integrated typologies, which are however not considered here.

For each typology, the terminal capacities along the transmission path are sequentially summed from exporter to importer nodes to determine the cable transmission capacities.[a] For onshore exporter nodes the default terminal capacities considered are 2 and 4 GW. The offshore wind farm terminal capacity is equal to the farm capacity adjusted by a multiplier, to account for the average availability of wind in the snapshots:

$$(4.1)\ wind\ link\ multipler = {\sum wind\ availability\ factor}\Big/_{number\ of\ snapshots}$$

The transmission capacities are then adjusted in two ways. First, capacities of lines connected to wind farms vary by ±10% and 20% to represent the over- or underplanting of wind farms [207]. Then, for all lines a further variation of ±10% of the capacity values increases the portfolio variety.

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[a] Equivalent to their thermal rating. All buses consider a voltage of 400 kV.

4.3.3. Costs and benefits

The model considers two cost types: generation operational costs (Figure 4.6), and transmission investment costs for cable and terminals (Appendix A). The optimal power flow calculation of the operation step of Figure 4.2 minimizes generation operational costs. Then, the transmission investment costs are used in the calculation of cost and benefit indicators in the investment step.

Two cost and benefit indicators are possible, the absolute net present value (NPV_a), and the net present value ratio (NPV_r). In each period the expansion with the highest positive NPV is selected using one of the indicators which considers benefits and costs over the lifetime of the assets:

(4.2) $NPV_a = (B_e - CI_e\ )$ (absolute net present value)

(4.3) $NPV_r = (B_e - CI_e\ )/CI_e$ (net present value ratio)

Where B_e and CI_e are the benefits and costs of investment of expansion e, respectively. The absolute and ratio NPV types reflect a preference in decision making for maximizing net welfare (the NPV_a) or for investing in an efficient plan which provides the most net welfare per investment (the NPV_r). The latter is relevant in a context of limited budgets of transmission system operators and discussions over their financeability [78].

The welfare governance constraints define which benefits and costs to consider. Three options are possible in a system with n nodes and an expansion involving a subset of n_{ep} nodes: no constraint and the Kaldor-Hicks and the Pareto ones. With no constraint the model accounts for net benefits (benefits minus costs) for all n system nodes. In its turn, the Kaldor-Hicks governance constraint considers only the subset of nodes n_{ep} involved in the expansion. In the Kaldor-Hicks constraint, the n_{ep} nodes must have positive net benefits *as a group.* Here, nodes with positive net benefits could *theoretically* compensate participating nodes with benefit losses, though they are not obliged to do so [208]. Lastly, in the Pareto governance constraint the net benefits are null if any of the n_{ep} nodes is a net loser (i.e. its net benefits are negative), because a net loser node could veto an expansion. Hence, the Pareto constraint is the strictest, and considers no compensation between nodes would be possible.

(4.4) $B_e - CI_e = \sum_i^{\mathrm{n}}(\Delta CS_i + \Delta PS_i + \Delta CR_i - \ CI_i)$ (No constraint)

(4.5) $B_e - CI_e = \sum_i^{n_{ep}}(\Delta CS_i + \Delta PS_i + \Delta CR_i - CI_i)$ (Kaldor-Hicks constraint)

(4.6) $B_e - CI_e = \begin{cases} \sum_i^{ep}(\Delta CS_i + \Delta PS_i + \Delta CR_i - CI_i)\, if\ \Delta CS_i + \Delta PS_i + \Delta CR_i - CI_i \geq 0 \mid \nabla\, i \\ 0, otherwise \end{cases}$

(Pareto constraint)

Where ΔCS_i is the consumer surplus, ΔPS_i is the producer surplus and ΔCR_i is the congestion rent, all measured as changes from the base to the expanded system (presented in equations 4.7-4.9). CI_i is the allocated nodal investment cost for node i. The model evaluates the present value of these costs and benefits using 25 years and a 4% discount rate.

Consumer and producer surplus and congestion rents are the usual economic benefit components [209]. For simplicity the subscript e is omitted for these components and for equations (1.7-1.12), which are specific to each expansion e nonetheless. For an inelastic demand, consumer surplus change is the difference in what consumers pay between two different system states. Producer surplus change is the change in the producer revenues that exceed generation costs (i.e. change in producer profits). Finally, congestion rent is the value of the flow through a line: the line flow, valued by the nodal price difference at the terminals. Hence, for each node *i* the change in these benefit components from the state *s-1* to *s* can be formulated as:

(4.7) $\Delta CS_i = \lambda_{i,s} * D_{i,s} - \lambda_{i,s-1} * D_{i,s-1}$ (consumer surplus)

(4.8) $\Delta PS_i = \sum_{g\in i} P_{g,s} * (\lambda_{i,s} - MC_g) - \sum_{g\in i} P_{g,s-1} * (\lambda_{i,s-1} - MC_g)$ (producer surplus)

(4.9) $\Delta CR_i = \sum_{l\in i} F_{l,s} * \left(\lambda_{i,s} - \lambda_{j,s}\right) - \sum_{l\in i} F_{l,s} * (\lambda_{i,s-1} - \lambda_{j,s-1})$ (congestion rent)

Where D_i is the nodal demand, λ_i is the nodal price, $P_g$and MC_g are the production and technology-specific marginal production cost of producer g, and F_l is the flow of line *l* connecting nodes *i* and *j.* The nodal prices are determined as the dual of the nodal balance constraint of the system operation optimization problem.

Finally, the cost of investment CI_e of a plan e with L lines and T terminals is the sum of its total cable CC and CT terminal investment costs:

(4.10) $CI_e = \sum_i^L CC_i + \sum_j^T CT_j$ (total investment costs)

(4.11) $CC_i = c_c * l_i * K_{l,i}$ (cable investment costs)

(4.12) $CT_j = c_t * K_{t,j}$ (terminal investment costs)

c_c is the cable unit cost (single cable type in M€/MW.km), while c_t is the terminal unit cost (M€/MW) which varies by node type (onshore, offshore wind farm or offshore hub as in Appendix A). K_l and K_t are the capacities of cables and terminals, and l is the cable length. Since a multiterminal HVDC grid needs converters only for points injecting or withdrawing power it reduces the requirements for converter (i.e. terminal) capacity. To model these investment savings, different rules for the terminal capacity K_t for point-to-point and multiterminal lines are considered, as in the Appendix A.

4.3.4. System state modeling

The system state for each period and snapshot is determined through the optimal power flow calculated with the Python for Power System Analysis (PyPSA) toolbox, version 0.4.2 [210]. The optimal power flow calculation determines the optimal dispatch of generators which minimizes generation operational costs. The dispatch cost of each generator is determined by the marginal generation costs (Figure 4.6). The linearized load flow model used (DC load flow) approximates power flows but is usual in transmission expansion studies and adequate for exploring long-term offshore grid transmission pathways [46,211]. Welfare changes are determined as differences between the base and expanded system states using the nodal prices provided by the optimal power flow solution. The model assumes generation technologies bid their marginal cost in a competitive central market, as in Hogan [209].

4.3.5. Verification

To ensure that the 'that the computer program of the computerized model and its implementation are correct' [212] the model has been verified through replication and extreme input testing. The replication was conducted for the optimal power flow and welfare components (consumer payments, producer surplus and congestion rents). Optimal power flows were compared with the MATPOWER package version 6.01b [213] and welfare components in MATLAB for all systems of the three case studies.

For input testing the wind farm and onshore terminal unit costs, cable unit costs, the discount rate, the hydropower capacity and the carbon price are varied. The extreme values lead to expected extreme model outputs. For example, no expansion is selected for high wind farm terminal unit costs, high discount rates or excessive hydropower capacity, due to excessively high costs or low benefits. Also, null cable costs lead to the selection of longer expansions instead of shorter split ones, since cable lengths do not affect investment costs in this case. Finally, high carbon prices incentivize connecting the low-carbon hydropower capacity of Scandinavia. The optimal power flow and welfare comparison files and results for the extreme input testing are available in Dedecca et al. [214].

4.3.6. Case studies data and model

The long-run marginal generation costs of Figure 4.6 and Appendix A are equal to the levelized operation, maintenance and fuel costs of the Energy Information Administration [215]. Those were converted using exchange rates and average carbon emission factors of the IEA [216,217]. Cable and terminal unit costs are obtained from E3G et al. [79]. The availability factors of the snapshots for each renewable generation technology are in Appendix A, and each of the snapshots represents 2920 hours. For comparison, according to the Department of Energy & Climate Change [218] the capacity factor for offshore wind farms in the UK in 2014 was 37.3%. The 2014 capacity factor of Danish offshore wind farms commissioned since 2009 amounted to 48% [219]. Demand and onshore generation capacities are based on the 2020 forecasts of the Ten-Year Network Development Plan scenarios of the ENTSO-E [220]. The starting interconnector transmission capacities are based on existing interconnectors [221]. The model source code and the simulation setup and results datasets are available in persistent repositories [214,222].

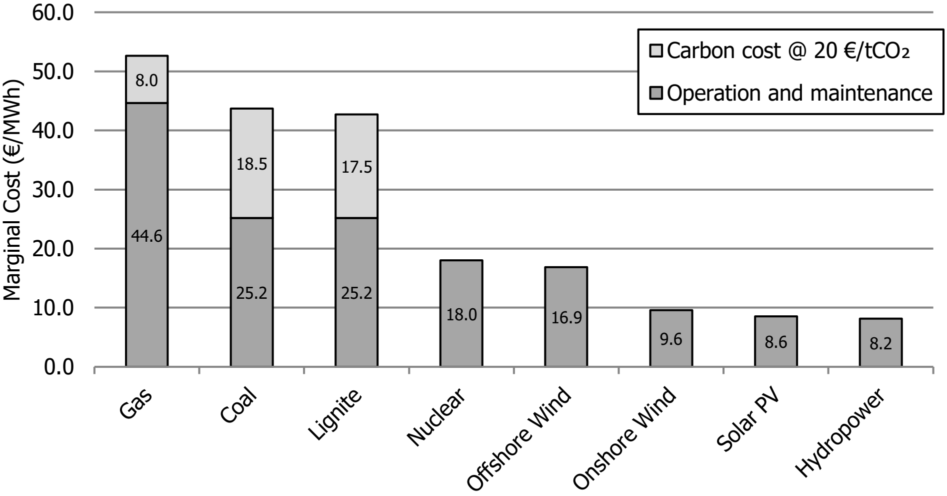


Figure 4.6: Marginal generation costs for the case studies

4.4. Results

This section first introduces the case studies, and then presents reference expansion pathways for each case study. This allows the categorization and illustration of factors observed as affecting the expansion selection, explaining why certain expansions are selected while others are not, and why the expansion pathways deviate from the reference cases. Finally, the factors and their interaction are discussed. Although the reference pathways facilitate the comprehension of the results, it does not mean they are more probable. This will depend on the actual realization of parameters in the future, on the cost and benefit indicator and on the governance constraint.

4.4.1. Case studies

A system of three onshore nodes is explored (Figure 4.7). This conceptual system is scaled to values comparable to the power systems of Northern Europe, with one offshore hub and two offshore wind farms. The onshore nodes represent Scandinavia (SC), the British Isles (BI) and continental Europe (CE) with the nodal generation capacities and demand of Appendix A.

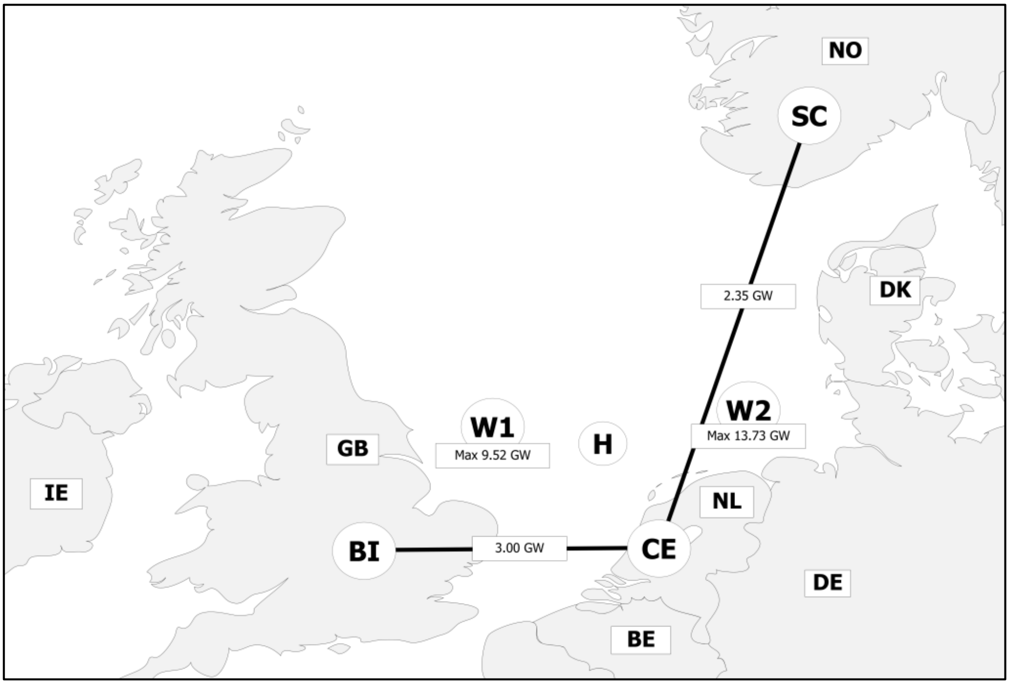


Figure 4.7: Three-onshore nodes system for case studies

To study this system, three case studies are designed and conducted: single period, simultaneous and sequential, with the last two being composed of two expansion periods. While in the single period case the capacities of both farms are introduced at the same time in the unique period, this introduction is split in the multi-period cases (symmetrically in the simultaneous, and asymmetrically in the sequential, Table 4.3). The multi-period simultaneous and sequential cases allow to study the expansion pathways from a path dependence perspective. An interesting future continuation of the research would be the iterative adaptation of these case studies making use of the results, such as large nodal price differences.

Table 4.3: Case studies presentation

Case	Single period	Simultaneous multi-period	Sequential multi-period
Expansion periods	One	Two	
Wind farm capacity addition	Total capacity of farms 1 and 2 on the single period	Half of total capacity of farms 1 and 2 in each period	Total capacity of farm 1 in period 1, and of farm 2 in period 2

4.4.2. Reference expansion pathways

The reference expansions of Table 4.4 are those which are selected in the case studies using central cost parameters (Appendix A), an NPV ratio indicator and no governance constraint. Figure 4.8 shows the reference expansion pathways for point-to-point HVDC lines, presenting the NPV_r of alternative expansions together with the selected expansion, for both periods. In the multiterminal simulations (analyzed in section 4.4.3) all lines not directly interconnecting onshore nodes are multiterminal, which may lead to a multiterminal meshed grid after multiple expansion periods. Appendix A provides the selected expansions for all case studies, with the full results dataset available in Dedecca et al. [214].

Table 4.4: Reference expansions

	Single-period	Sequential multi-period	Simultaneous multi-period
Point-to-point	West split	Farm 2 radial	West split
	-	West IC split	Farm 1 hub
Multiterminal	Continent split	West IC split 2	Hub
	-	West IC split	Nordic split

1.1.1.1. First period reference expansions

In the single period case the *west split* expansion is selected, with an NPV_r of 3.3 – hence the expansion net benefits amount to 330% of the investment cost of 7.5 B€ (top left of Figure 4.8). Although the *west split* expansion through farm 2 is not as direct as a radial typology, it combines the onshore systems interconnection and offshore wind farm connection grid functions efficiently. Through the same lines it connects all wind farms and provides two export routes from Continental Europe to the most expensive onshore node, the British Isles.

The same *west split* expansion is selected in the 1st period in the simultaneous case – indeed, since in this case both wind farms are introduced at the same time, the difference between the single period and the simultaneous cases is the total capacity that is introduced in the first period (half, in the simultaneous case). However, costs do not decrease linearly with the offshore wind capacity, so that investment costs decrease by only 25%. Thus, the simultaneous case NPV_r is 2.4, lower than the single period value of 3.3.

The sequential case with its deferred introduction of wind farm capacity selects a different expansion, the *farm 2 radial,* with an NPV_r of 3.2. Here, since only wind farm 2 is beneficial to connect, this expansion separating the grid functions is the preferred one. It connects the wind farm to the closest onshore node, and interconnects the importing British Isles to the other systems who have less expensive generation technologies (the Scandinavian hydropower and Continental Europe's new wind farm 2).

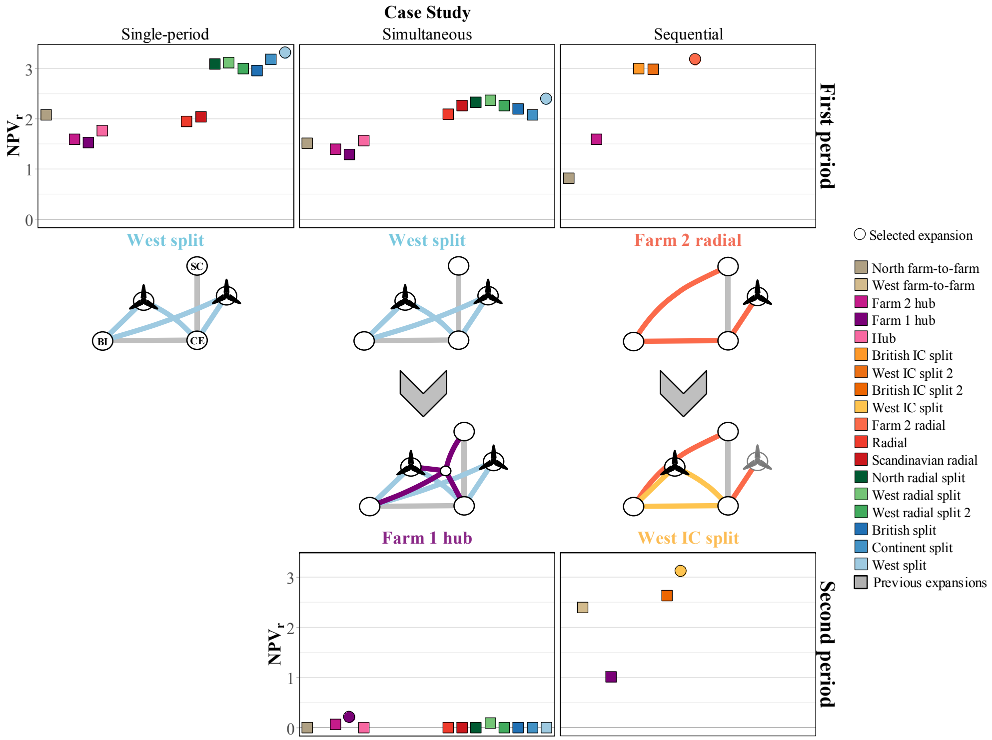


Figure 4.8: Reference expansion pathways for point-to-point-lines

1.1.1.2. Second period reference expansions

Only the simultaneous and the sequential cases simulate a second period expansion. In the former the *farm 1 hub* expansion is selected, creating a meshed grid complementary to the previous *west split* (center of Figure 4.8). It is a particular case which connects only the wind farm closest to shore, due to the balance between central values of onshore and wind farm terminal investment costs. Generally, the simultaneous case leads to a highly meshed grid with two expansions combining the interconnection and farm connection functions (Appendix A), due to the symmetric addition of offshore wind capacity.

For the sequential case the w*est IC split* expansion is selected, following the *farm 2 radial* expansion of the 1st period. It joins the new wind farm 1 through the two closest nodes (which also have the highest power prices), and adds a conventional interconnection between these nodes. The expansion pathway for the sequential case leads thus to an offshore transmission system that is less meshed than in the simultaneous case, because the asymmetric offshore wind addition favors more radial typologies.

Interestingly, while in the 2nd period the sequential expansion has an NPV_r of 3.11, for the simultaneous expansion this falls to 0.2. The simultaneous expansions generally present a lower NPV_r because investment costs do not decrease linearly with the reduced wind farm capacities.

4.4.3. Investment management factors

After presenting the reference expansions, now an analysis of which factors lead to alternative pathways and which are the mechanisms they act through is conducted (Table 4.5). Certain factors arise from the model, while others emerge from the actual simulation or from the characteristics of different typologies.

Table 4.5: Investment management factors and their mechanisms

	Factor	Mechanisms
Modeling	Cost structure	Higher cable costs favor shorter lengths Higher terminal investment costs favor expansions with lower terminal capacities
	Line technology	Multiterminal lines have reduced investment costs, but parallel multiterminal lines may restrict flows
	NPV types	The NPV_a favors the maximum net benefit, independently of the investment cost The NPV_r favors investment efficiency by maximizing net benefits over investment costs
	Governance constraints	Kaldor-Hicks and Pareto constraints rule out expansions which may have higher social net benefits
Simulation	Path dependence	Previous investments in expansions change the system and affect the following periods
	Wind farm installation timing	New wind farms are beneficial to connect, so the timing affects expansions
	Candidate exhaustion	Previous expansions or higher investment costs may lead to no beneficial expansions
	Expansion characteristics	Even for the same typology expansions partly differ in capacities and lengths
Typology	Grid functions integration	Function integration may lead to lower investment costs but also higher line congestion
	Terminal capacities levels	Higher terminal capacities increase transfer capacities but require higher investments

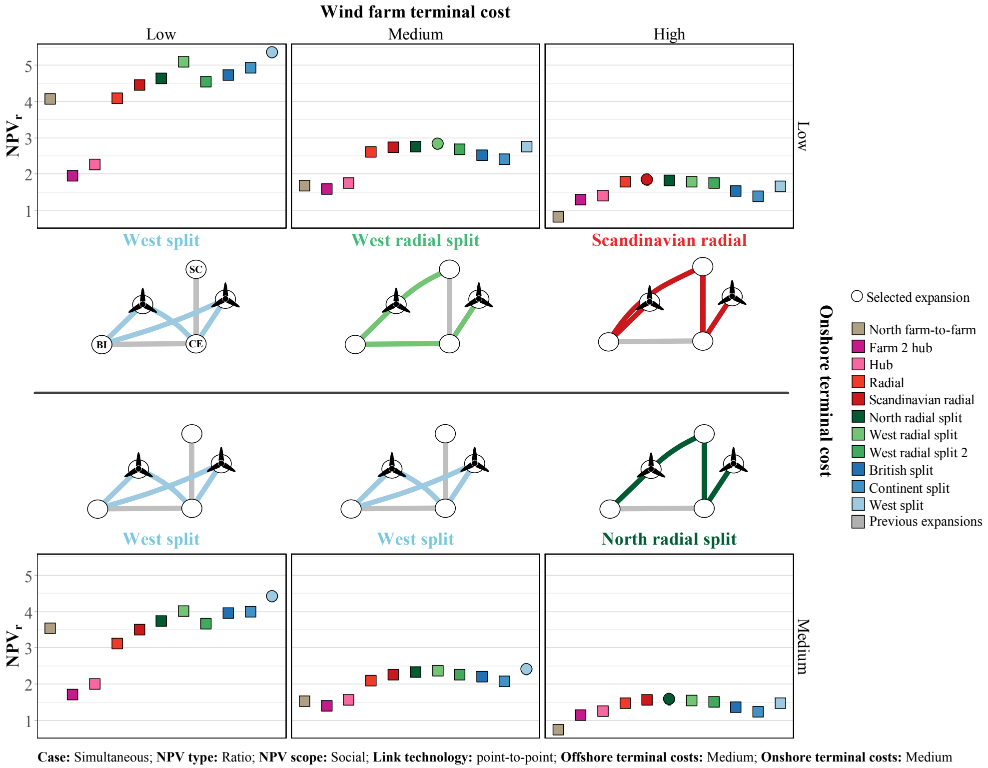
1.1.1.3. Modeling factors

Modeling factors arise from the input data and model formulation. The first modeling factor is the cost structure: the cost parameters and the rules for determining terminal and cable capacities. It directly affects the expansion investment costs and therefore its net benefits (Appendix A). The second modeling factor is the line technology: point-to-point or multiterminal (each with advantages and disadvantages as described in section 2.2.1). The last modeling factors are the governance constraints and NPV types of section 4.3.3, which respectively rule out some expansions and affect how net benefits are evaluated.

Cost structure

The cost structure mechanisms are straightforward: higher terminal investment costs favor expansions with lower terminal capacities, and higher cable costs favor shorter typologies (such as radial ones). Nonetheless, since expansions compete for selection, the comparative values for terminal (onshore, wind farm and offshore hub) and cable costs is also relevant for the expansion pathway.

Thus, in the first period of the simultaneous case, increasing wind farm terminal investment costs favor increasingly radial typologies: from *split* to *radial split* to *radial* (first row of Figure 4.9). However, this is countered by onshore terminal costs increases, as shown in the second row of Figure 4.9. Here, even with high wind farm terminal costs only an expansion belonging to the *radial split* typology occurs.

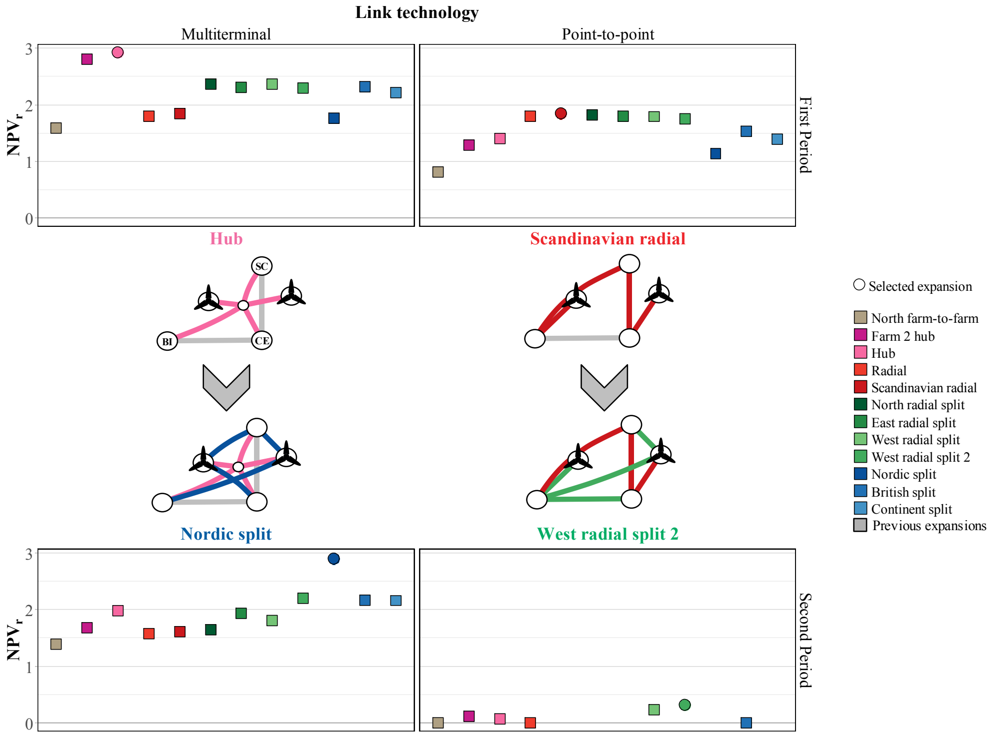


Increasing wind farm terminal costs lead to more radial typologies. This is countered by an onshore terminal cost increase in the second row.

Figure 4.9: Influence of comparative terminal investment costs

Line technology

Expansions with multiterminal lines benefit from reduced investment costs due to a reduced number of converters or converter capacity, but may restrict flows. Point-to-point expansions on the other hand can be more expensive but do not restrict flows (section 2.2.1). Ultimately the investment savings of multiterminal lines outweigh the possible flow restrictions, favoring the *hub* and *split* typologies. Hence, in the simultaneous case, multiterminal lines lead to the selection of the *hub* expansion instead of the *Scandinavian radial* expansion (first row of Figure 4.10). For the same case, in the second period the *Nordic split* expansion is chosen. This because it benefits from investment savings while limiting the flow restrictions to which a more logical, shorter expansion (without crossing lines) would be exposed. Therefore, seemingly paradoxical expansions may actually be the most beneficial, something that can be accounted for only with load flow modeling.



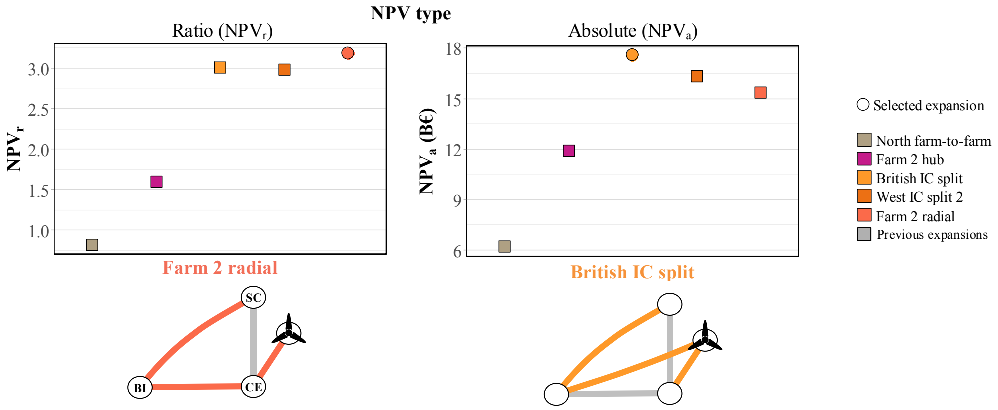
Case: Simultaneous; ***NPVr* with social scope**; **Wind farm terminal costs**: High; **Onshore terminal costs**: Low

Multiterminal lines favor more integrated expansions belonging of the hub and split typologies.

Figure 4.10: Line technology factor

NPV types

The NPV_a favors expansions with higher terminal and cable capacities, which provide higher net benefits, while the NPV_r weighs net benefits against investment costs. Thus the NPV_r selects the *west split* expansion in the single period and simultaneous reference cases due to their efficient function integration. In other simulations the NPV_r can also select expansions which are less congested in high wind availability, or that have lower terminal and/or cable capacities. Figure 4.11 contrasts the first period selection of the sequential reference case with that of an NPV_a criteria.



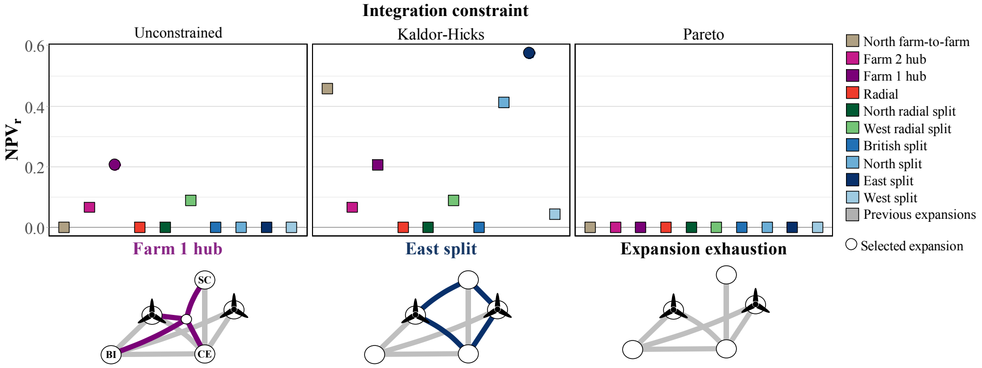
Case: Sequential; **First period**; **Link technology**: point-to-point; ***NPVr* with social scope**; **Wind farm terminal costs**: Medium; **Onshore terminal costs**: Medium

The NPV_r selects more efficient expansions while NPV_a usually have higher transmission capacities.

Figure 4.11: *NPV* types

Governance constraints

As seen, the Kaldor-Hicks and Pareto governance constraints restrict the acceptable expansions, with the Pareto constraint being the most restrictive (forbidding welfare losses for all participating nodes). Hence, in the second period of the simultaneous case, the selected reference expansion is the *farm 1 hub.* This while the Kaldor-Hicks constraint selects the *east split*, and the Pareto constraint selects no expansion (Figure 4.12).

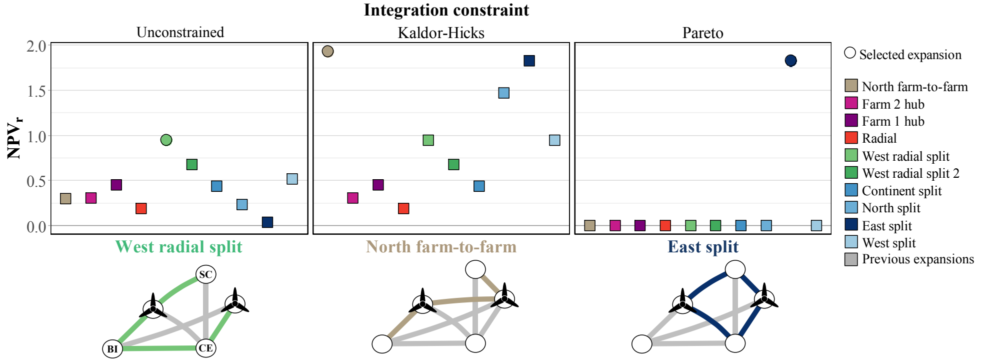


Case: Simultaneous; **Second period**; **Link technology**: point-to-point; ***NPVr***; **Wind farm terminal costs**: Medium; **Onshore terminal costs**: Medium

Different constraints restrict certain expansions or increase the net benefits by excluding loser nodes.

Figure 4.12: Governance constraint

However, the Kaldor-Hicks constraint may select a different expansion by excluding (not connecting) a welfare-losing onshore node, and provide a higher NPV overall. Increasing constraints lead thus to complex changes in expansion selection – no dominance of expansions exists between constraints. Thus, for low wind farm and onshore terminal investment costs, the *west radial split* is selected with no governance constraint. The Kaldor-Hicks constraint selects the *north farm-to-farm* which excludes Continental Europe, and the Pareto constraint selects the *east split* which excludes the British Isles (Figure 4.13).



Case: Simultaneous; **Second period**; **Link technology**: point-to-point; ***NPVr***; **Wind farm terminal costs**: Low; **Onshore terminal costs**: Low

The Kaldor-Hicks expansion does not comprise Continental Europe, and the Pareto expansion excludes the British Isles.

Figure 4.13: Non-dominance of expansions for *NPV* constraint

1.1.1.4. Simulation factors

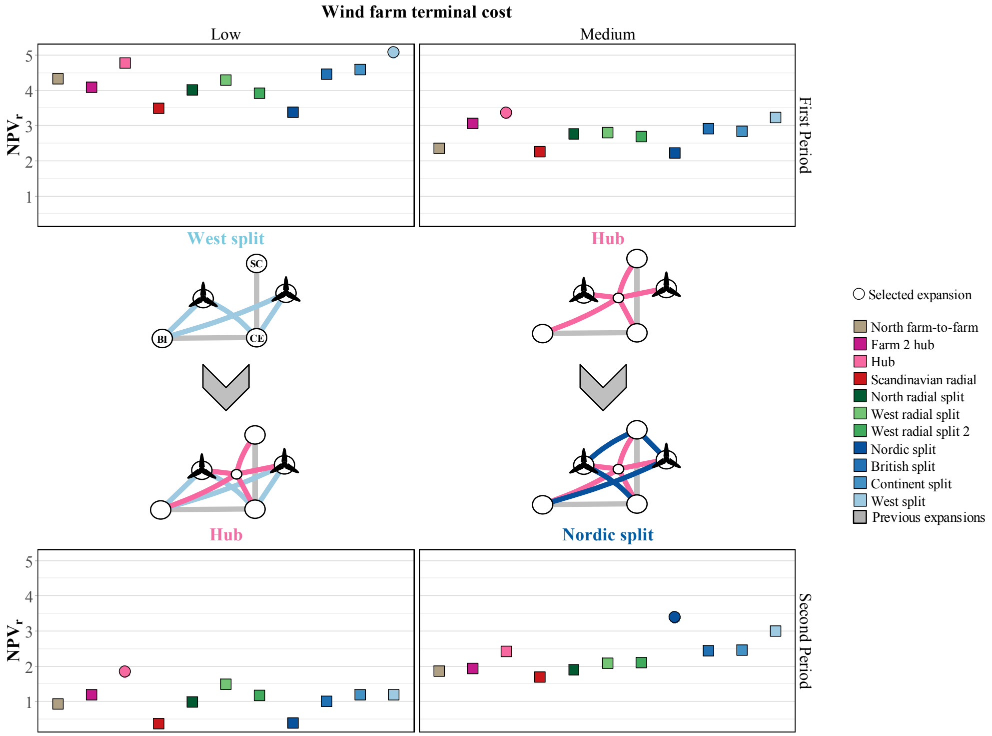
Simulation factors are dynamic factors that can be observed from the pathways of the offshore grid. Path dependence is one of the four simulation factors, and as described in section 2.3 the system can be locked into a certain expansion pathway in the absence of external influences. This interacts with the second simulation factor of wind farm installation timing, so that systems where the final offshore wind capacity is the same may end up with different grids depending on how this capacity is introduced. Also, no expansion may fulfil a given NPV criterion due to previous investments or to a change in cable or terminal investment costs, causing candidate exhaustion (the third factor). Finally, the characteristics of different expansions such as line lengths and terminal capacities affect the investment, even for expansions belonging to the same typology.

Path dependence

Path dependence leads to a higher variation of selected expansions in the 2nd period. Also, path dependence leads to non-monotonic $NPVs$: higher cost parameters do not necessarily reduce $NPVs$ as in single period expansions, because expansions in previous period affect the NPV of following periods.

A strong path dependence can be observed in the exploratory model. While for all runs the single period case study selects only two expansions, the sequential case selects six, and the simultaneous case fifteen different ones (Appendix A). The importance of path dependence increases due to the existence of near-optimal solutions in transmission expansion planning problems. In these problems, changes in the model can easily lead to the selection of a different expansion in the following period. Thus, in the reference expansion pathways of Figure 4.8 near-optimal expansion plans have an NPV_r close to the selected expansion. Methods such as scenario planning, sensitivity analysis and robust optimization can address near-optimal solutions in transmission expansion planning. The simulation approach also addresses near-optimal expansions, since the aim is not to propose a single, optimal expansion pathway, but instead to explore the factors leading to different pathways.

However, the observed path dependence is strong but not absolute, so that complementarity between expansions can be observed in the simulations. Hence, for the simultaneous case with multiterminal lines, the *hub* and *Nordic split* expansions are chosen in the first and second period respectively. But low wind farm terminal investment costs lead to the selection of the *west split* and *hub* expansions, respectively (Figure 4.14). In this way, *hub* and *split* typologies exhibit complementary benefits and their selection is only partly affected by path dependence.



Case: Simultaneous; **Link technology**: Multiterminal; ***NPVr* with social scope**; **Onshore terminal costs**: Medium

The split and hub typologies are partly complementary.

Figure 4.14: Path dependence and expansion complementarity

Wind farm installation timing

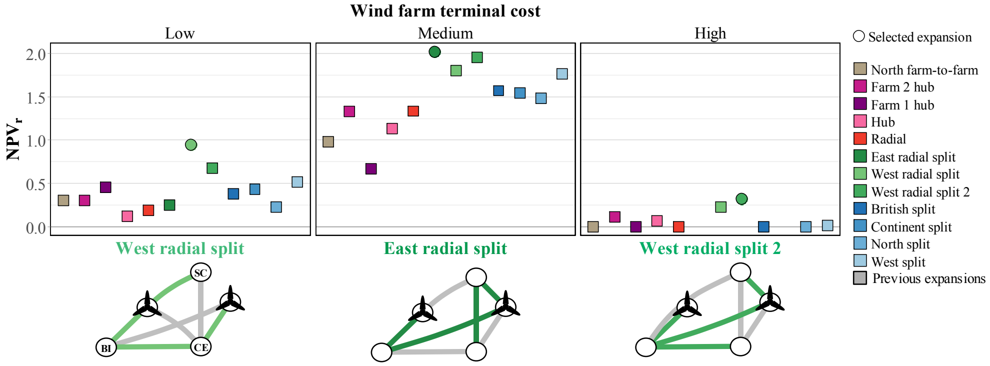
The wind farm installation timing directly affects the expansion selection, for generally it is most beneficial to only connect all wind farm locations whose installed capacity increases. Hence, in almost all simulations any new wind farm is immediately connected, while no expansion connects wind farms of unchanged capacity (Append A). This illustrates the importance that the timing of actual offshore wind development in the Northern Seas can have on the offshore grid expansion pathways.

Candidate exhaustion

As indicated, due to previous investments or a change in investment costs it is possible for no expansion to have a positive NPV (Figure 4.12). Candidate exhaustion occurs more easily with the more restrictive Kaldor-Hicks and Pareto constraint, and is rarer with multiterminal lines because investment savings usually improve the NPV of some expansions. This is illustrated in Figure 4.12, where the Pareto constraint leads to expansion exhaustion – though the NPV_r of expansions considered under the Kaldor-Hicks constraint are not necessarily lower than under no governance constraint.

Expansion characteristics

Expansions of the same typology have different NPVs, due to characteristics of their own or of the system (such as node location or generator capacities and marginal costs). For a same typology, expansions may exclude certain nodes, and terminal capacities may change as well as line lengths and capacities. Thus, for example with low terminal onshore costs in the 2nd period of the simultaneous case, only radial split expansions are selected – but three different ones (Figure 4.15).



Case: Simultaneous; **First period**; **Link technology**: Multiterminal; ***NPVr* with social scope**; **Onshore terminal costs**: Low

Figure 4.15: Different characteristics for expansions of the same typology

1.1.1.5. Typology factors

Although expansions have individual characteristics, each typology also has distinct features. Therefore, the typology characteristics of Table 4.6 are the last category of factors, comprising the levels of grid functions integration and terminal capacities.

Table 4.6: Function integration and terminal capacities for typologies

Typology	Grid functions integration	Onshore terminal capacity	Wind farm terminal capacity
Radial	Low	Medium	Low
Hub	High	Low	
Split	High	High	
Radial split	Medium	Medium	
IC split	Medium	Medium	
Farm-to-farm	High	High	

First, by allowing conventional or integrated lines, typologies have different levels of integration of the grid functions of offshore wind power connection and power systems interconnection. Integrated connectors and interconnectors combine functions more and require less cabling (e.g. a split expansion has shorter lengths than a radial one) and thus lower cable investment costs. On the other hand, the grid function integration means an integrated path serves to transmit both offshore wind power and power exports from onshore nodes, which increases the chance of congestion. Therefore, a higher grid function integration trades off cable investment costs advantages and possible operational disadvantages.

Second, terminal capacities differ for each typology and are influenced by multiterminal lines. With conventional connectors offshore wind power terminals need to be dimensioned only for the wind farm exports. For integrated lines without multiterminal line technology, these offshore terminals need to account not only for the wind farm exports but also for any incoming interconnectors from exporter onshore nodes. Moreover, importing onshore terminals may need to be dimensioned for the capacity of incoming lines. Thus, typologies with lower terminal capacities and/or benefiting from multiterminal line technology (following Appendix A) have advantages in terminal investment costs. However, a more sophisticated model could differentiate between converter capacity needed to connect offshore wind farms to wind hubs, and the terminal capacity of these hubs.

An example is the *split* typology, which highly integrates the grid functions and has high onshore and wind farm terminal capacities. It shortens cable lengths and thus may allow for lower investment costs for long distances, at the expense of possible congestion of transmission and susceptibility to high terminal investment costs. As such, it could be adequate for long interconnections with high complementarity between offshore wind power generation and power exchanges. It is thus chosen much more often in the simultaneous than the sequential case (Appendix A). Also, it benefits from multiterminal investment savings, possibly avoiding the occurrence of candidate exhaustion, though it has high terminal capacities.

4.4.4. Pathways of the Offshore Grid

Multiple factors that affect the expansion pathways were presented, but path dependence is especially important for the grid development over time. The fact that expansion pathways exhibit strong but not absolute path dependence is demonstrated, that is, expansion selection is strongly influenced by previous expansions, although other factors also play a role. Hence, on the one hand, Figure 4.8 illustrates how the grid pathways vary significantly, even for the reference case studies. On the other hand, hub and split expansions may complement each other for multiterminal lines, so that after two periods both typologies are built, but in different order (Figure 4.14). This is in accordance with the path dependence characteristic of infrastructures indicated in section 2.3.

Also, factors do not affect pathways equally for all expansions, not even those belonging to the same typology. Some factors affect homogeneously expansions of the same typology (the NPV types, terminal investment costs, and the line technology). Other factors interact more with specific expansions, regardless of their typology (e.g. the governance constraint, cable investment costs).

As seen, studies indicate the Northern Seas grid will develop gradually [1]. Since the grid exhibits strong path dependence, advocates call for anticipatory investments to avoid lock-in and keep more expansion options open [51,68,223]. However, innovations in HVDC technology will affect the factors and therefore the typologies and expansions differently. High investment costs lead to less integrated typologies (such as the *radial*) or point-to-point lines being preferred. Additionally, it is not only the absolute value of investment costs that matters, but also their relation. The need for DC breakers, DC/DC converters and multiterminal control strategies will not be the same for all typologies, for they have different levels of grid functions integration and terminal capacities. Thus, different innovation rates for the components of multiterminal HVDC transmission will affect the comparative performance of expansions.

The combination of path dependence with the unequal effect of HVDC innovations highlights the importance of anticipatory investments, cost reductions and the interoperability for HVDC technology. These are required for developing an integrated grid sooner than later and not locking out beneficial expansion pathways.

4.5. Conclusions

Among the energy modeling approaches, simulation through the use of myopic optimization models allows to explore the consequences of governance constraints in the offshore expansion pathways. Thus, *OGEM models these governance constraints to simulate sequential offshore generation and transmission investment periods* shaping the expansion pathways for the offshore grid.

Using a conceptual case study, this chapter has partially addressed the third subordinate research question of how governance barriers affect expansion pathways towards an integrated offshore grid. *OGEM develops two categories of governance constraints* to model these governance barriers: the welfare and the integration governance constraints. Moreover, this first case study leveraging OGEM identified three categories of investment management factors: modeling, simulation and typology. These factors organize the complex system behavior that forms the offshore expansion pathway. Results stress the *asymmetry of the distribution of costs and benefits (as evidenced by vetoes to integrated expansions), the interaction of the integrated governance constraints with transmission lines types and technologies, and the importance of path dependence.* This raises a number of principles for the design of governance frameworks for offshore grids.

Typologies perform the grid functions of connection and interconnection with *different levels of integration and terminal capacities*, with also modeling and simulation factors affecting the transmission expansion pathways. Results indicate that planning of the offshore grid will need to consider these factors when choosing the preferred expansion. Previous models of the Northern Seas offshore grid applying perfect foresight optimization did consider the link technology, costs and benefits types and scopes, and factors such as the expansion characteristics and the timing of offshore development. However, they did not simultaneously address all the factors identified. *The simulation model considers the typologies and factors to create expansion pathways and understand the grid path dependence*, which are shown to be strong but not absolute. The *existence of near-optimal expansion plans reinforces the usefulness of this simulation approach.*

Cooperation is a central component both of Energy Union proposals and of calls for the development of an integrated offshore grid in the Northern Seas. However, the literature indicates that despite ambitious visions, cooperation and governance are major barriers to a more integrated development, and as a consequence grid development has been conducted nationally or bilaterally. A long time has passed since the first calls for an offshore grid in the end of the last decade. Since then many interconnectors and wind farms were developed, already taking the grid to certain pathways. *The lack of an adequate governance framework and not evaluating the impact of HVDC innovations will continue to lock out possibly beneficial pathways using integrated expansions*, together with other issues not studied in this chapter such as HVDC technology vendor interoperability and standardization issues.

This is unwelcome, given that *innovation and the integration of energy markets are two of the dimensions of the Energy Union*. Given the potential of the offshore grid to be a major contributor to this Energy Union, *HVDC technology innovation must be a part of the Union's strategy*. Also, OGEM indicates the importance of considering multiple expansions plans with different typologies, but also that these plans have individual advantages and drawbacks. Moreover, recommendations on specific transmission expansion plans require modeling the European power system in greater detail, as indicated in these conclusions. *The ENTSO-E is currently the organization which has both the mandate and the resources and data necessary to conduct such an exercise*. Academia has researched the transmission expansion planning of the Northern Seas offshore grid, even recommending specific plans. It can *continue to support planners and policy makers in such a manner, with simulation complementing the usual optimization approaches*.

Hence, *planning of the Northern Seas offshore grid in the framework of the Energy Union should be done regionally through the ENTSO-E*, considering multiple typologies and the factors of the study. Planning should choose between benefit maximization or efficiency (i.e. different NPV types), and consider transmission technologies and their innovation rates, expansion and system, and the interests of countries and actors. After this regional planning, *individual projects can then be evaluated and implemented*.

Next, chapter 5 continues to address the third subordinate research question by developing the integrated governance constraints, including the expansion of generation and deploying a more detailed case study.

5 North Sea generation and transmission expansion pathways[a]

5.1. Introduction

The current chapter continues to address the third subordinate research question: how do governance barriers affect expansion pathways towards an integrated offshore grid? The present case study thus researches the impact of integrated governance constraints on the generation and transmission expansion of the European North Sea offshore grid from 2030 to 2050. As seen in chapter 2, European expansion planning originates at the national level and does not consider integrated lines. The networked, multi-level and multi-actor aspects of European expansion planning argue for decision-making through governance. Moreover, modeling studies have largely left the governance barriers for integrated lines unaddressed and do not use simulation approaches, as the review of chapter 3 indicates.

Chapter 4 developed an offshore transmission expansion conceptual case study analyzing several investment management factors in the categories of modeling, simulation and typologies. Particularly, the conclusions stress the welfare distribution asymmetry, the interaction of the transmission lines technologies and type (integrated or not) and the importance of path dependence. This allows the development of governance principles for the offshore expansion planning, concerning the need to consider a comprehensive candidate portfolio, the path dependence and lock-in, and the effect of the existing welfare distribution asymmetry between countries and actor groups

The version of OGEM presented in the present chapter further develops the modeling of the costs and benefits distribution and the complexity of integrated site planning and development barriers to deploy an integrated offshore grid. This is the first application of the integrated governance constraints described in section 4.2 on a more detailed system than that of chapter 4 and to include the co-planning of generation and transmission. Furthermore, this version of OGEM includes generation expansion and eliminates the expansion portfolio creation and investment management heuristics of chapter 4, which are instead handled by the optimization problem. Also, while chapter 4 included only two expansion periods, this chapters studies three ten-year expansion periods from 2030 to 2050. To address long-term uncertainty this chapter incorporates the five scenarios of the e-Highway2050 [87] project for the European power system expansion.

The rest of the chapter is structured as follows: section 5.2 presents the methodology and data (a full model formulation can be found in the Appendix B, and the data and source code are public). Then, section 5.3 presents a

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[a] This chapter is based on Dedecca et al. [20] with modifications.

comparative analysis of the unconstrained and constrained offshore expansion pathways, discussing the effect of the integrated governance constraints. Finally, section 5.4 concludes by deriving principles for the design of offshore expansion planning governance frameworks.

5.2. OGEM for transmission and generation expansion

The version of OGEM for this chapter optimizes offshore transmission and generation investments and the operation of the European power system for sequential expansion planning periods. It is a deterministic sequential-static (myopic) Mixed-Integer Linear Programming (MILP) model. The myopic expansion planning approach of chapter 4 is improved following the recommendations of Dedecca et al. [21], by also optimizing investment and by including generation expansion.

Thus, this section first presents the overarching structure of myopic optimization through sequential expansion periods following the general flow of figure 4.1. Then, the formulation of each expansion period is presented. The integrated governance constraints are the main contribution of OGEM, and are covered in detail next. Finally, the case studies data are presented, while the final part of the section covers verification and validation.

5.2.1. Myopic approach

The full model formulation of Appendix B is implemented through a mixed-integer modification of the Python for Power Systems Analysis (PyPSA) toolbox [210]. Selected candidate transmission lines are added in each period as existing lines in the following period, and the initial system for 2030 is based on the e-Highway2050 project.

For each expansion period the model defined by the objective function (5.1) and constraints (5.2-5.19,5.22-5.23) is run three times. Each run represents investment decisions in the 2030, 2040 and 2050 decades (each modelled by a representative year), as in Figure 5.1. First, a full-year (8760 snapshots) system operation optimization is conducted, without any candidate line (step 1), so in this case each snapshot represents one hour of the system operation. This establishes the baseline system operation to calculate the net benefits of the offshore expansion.

Before optimizing the expansion of the offshore system, the number of snapshots is reduced (step 2) to make the expansion optimization computationally tractable. To select representative snapshots, snapshots are clustered using a k-medoids algorithm with prices for all system nodes as input data. This means snapshots are grouped in order to reduce the within-cluster nodal price differences. The time series representing load and renewables availability are then scaled, so that the reduced-snapshot time scales are equivalent to the full-snapshot ones. Load is scaled by an average factor considering mean and peak load, while renewables are scaled by the peak availability. More information on clustering and scaling techniques can be found in Nahmmacher et al. [224], Härtel et al. [225] and Kristiansen et al. [226].

Also, since the order of snapshots is lost with the clustering, the dispatch of storage units from the first optimization is fixed. There is therefore no investment in storage technologies, and thus the possible substitutability or complementary interactions of generation and storage expansion is not analyzed, such as in Bustos et al. [227].

The investment and operation optimization problem is solved with the one hundred clustered, representative snapshots (step 3). This provides the generation and transmission investments for the current expansion period.

This investment selection is fixed and storage units unfixed in the intermediary step 4 in order to run a full-year operation optimization model including these selected offshore candidate lines and wind farms (step 5). This allows the comparison of the operation of the expanded system against the baseline system of the first optimization, to calculate the net benefits of the expansion.

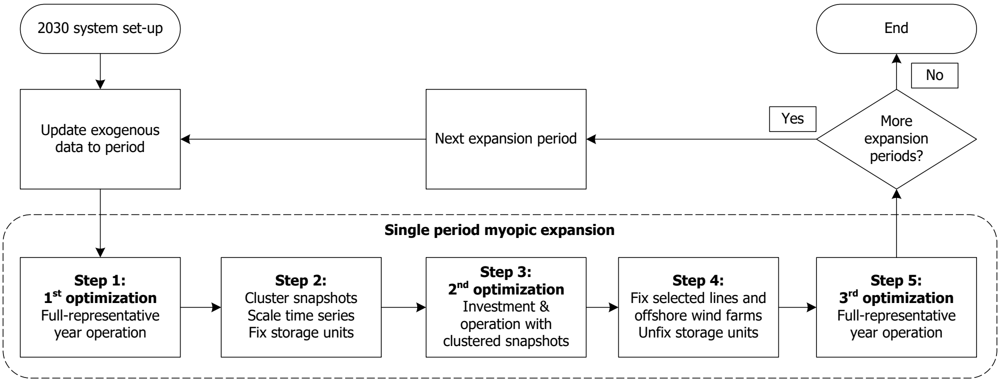

Figure 5.1: Sequential expansion planning model flowchart

5.2.2. Formulation

Figure 5.2 presents the main decision variables and the conceptual formulation of the expansion model for a single period, while the exact variables and formulation are available in the supplementary material.

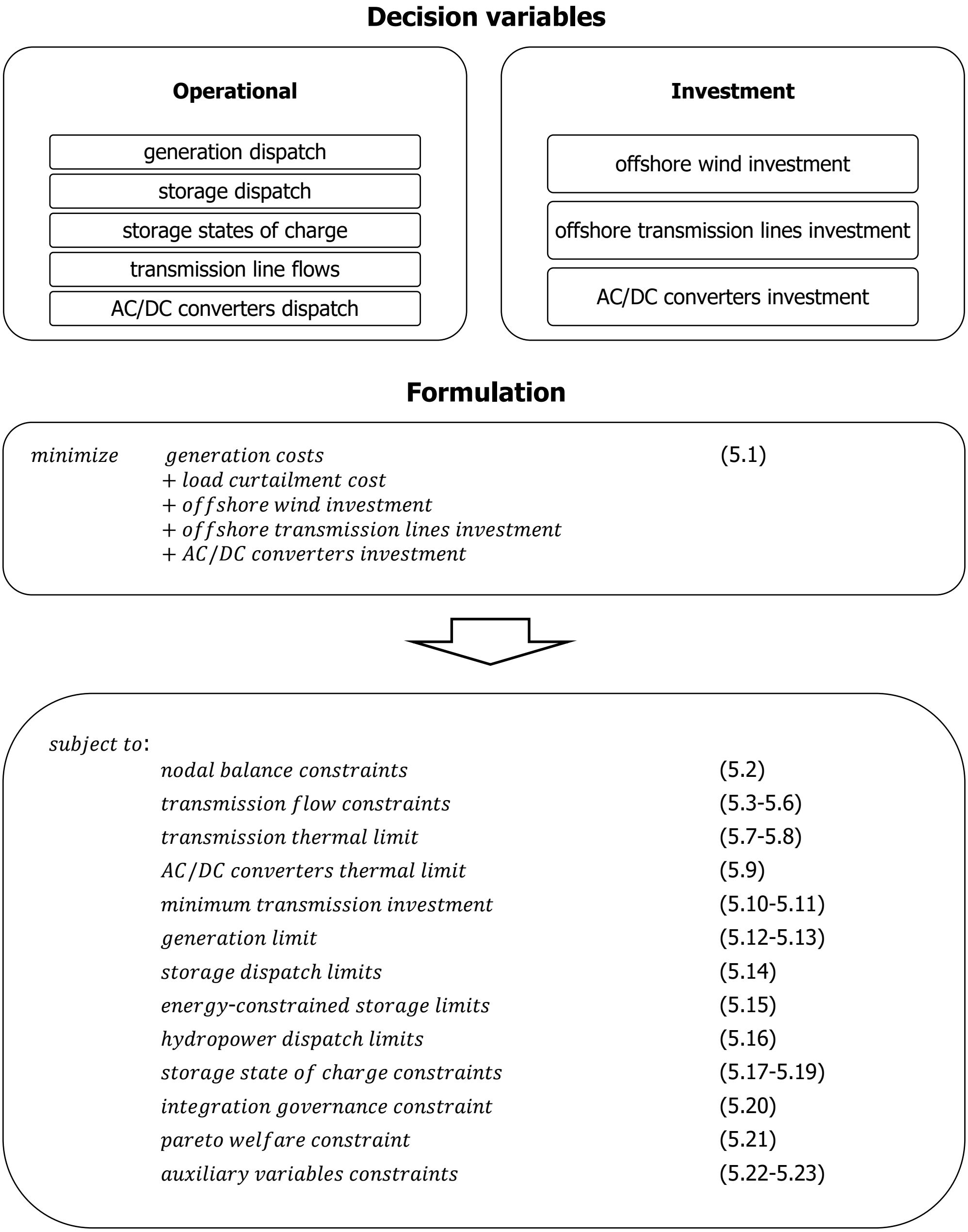

Figure 5.2: Single period expansion model formulation

The objective function (5.1) and constraints (5.2-5.19) with (5.22-5.23) represent the expansion problem for a single period, with the optional integrated governance constraints (5.20-5.21). The objective function minimizes the sum of investment and operation costs, and a balance constraint is imposed for every node considering transmission, demand, generation and storage (equation 5.2). Linearized power flow constraints for HVAC and multiterminal HVDC lines due to voltage limits (equations 5.3-5.6) and thermal capacity limits for all transmission technologies (equations 5.7-5.9) are applied. Offshore generation investment is modelled through continuous variables. Additional constraints comprise generation and storage capacity and energy limits (equations 5.12-5.19).

5.2.3. Integrated governance constraints

As indicated in section 4.2.1, the integrated governance constraints represent governance barriers to integrated transmission lines. To analyze the effect of the integrated governance constraints, a comparative structure is used between the constrained expansion pathways and the unconstrained ones. Every expansion pathway (constrained or not) uses the methodology of Figure 5.1 and Figure 5.2, and for constrained pathways a single integrated governance constraint is activated at a time.

The integration constraint (equation 5.20) represents the planning complexity by limiting the number of integrated lines built for any node in a given expansion period to a certain limit $\in \{0,1,\infty\}$.

(5.20) for each node: $\sum_{incoming\ offshore\ line} \text{binary investment variable} \leq integration\ limit$

The particular value of this limit leads to two types of integration constraint. First, the complex integration constraint limits expansions to one integrated line per node per expansion period. Then, the disintegrated constraint prohibits any integrated line being built at all. This limit does not constrain the investment in conventional offshore transmission lines.

Then, the Pareto welfare constraint (equation 5.21) represents the distribution of costs and benefits by modeling the veto of a North Sea country to investments in integrated lines in their territory. When it is active, any country whose welfare decreases relative to the base welfare does not invest in any integrated lines [21]. The cooperation variable of equation (5.23) indicates for each North Sea country whether it invested in any integrated line or not.

(5.21) for each North Sea country:

$$\sum \text{producer surplus} + \sum \text{storage surplus} + \sum \text{congestion rent} + \sum \text{consumer surplus}$$

$$- \sum offshore\ lines\ investment - \sum AC/DC\ converters\ investment - \sum offshore\ wind\ investment$$

$$+ disjunctive\ parameter * (1 - cooperation\ variable) \geq 0$$

Here, the welfare components are the producer surplus (including of storage units), consumer surplus and congestion rent as in Hogan [209], always compared to a case without offshore expansion. Hence, welfare increases stem from system operation gains due to offshore expansions, while net benefits amount to the total welfare gains minus investment costs for all expansion periods.

5.2.4. Data

All non-confidential input, output and figures and appendices data is available in Dedecca et al. [228], with large files available upon request. The code is also open-source [229].

5.2.4.1. Scenarios for the onshore power system

To address uncertainty the five scenarios of the e-Highway2050 project are utilized. They were selected in the project to form alternative, representative futures to achieve the almost complete decarbonization of the European power system by 2050, as indicated in Table 5.1. These scenarios define the exogenous expansion of the onshore power system, while the offshore generation and transmission expansion is determined endogenously by the model[a]. This results in different levels of demand, onshore interconnection and deployment of carbon capture and storage, nuclear and renewable energy sources technologies. Appendix B indicates the 2050 merit order curve for each scenario, with clear differences in the cost and capacity of generation technologies, and load levels.

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[a] The scenarios differ in macro-economic and technological aspects (growth, demographics, fuel costs, carbon capture and storage maturity), preferences (regarding nuclear and distributed generation) and policies (towards renewable energy sources and regional and national energy independence).

Table 5.1: e-Highway2050 onshore scenarios

Scenario	Description	Demand	Nuclear	Fossil fuels with CCS	Onshore interconnection	Onshore renewables
Large-scale RES	High RES deployment with interconnection and nuclear	Very high	High	None	Very high	High
100% RES	Highest RES deployment with interconnection and only combined cycle gas as conventional generator	High	None	None	Very high	Very high
Big & Market	Medium RES deployment with nuclear and some CCS	High	High	Medium	Low	Medium
Small & Local	High local RES deployment with little interconnection	Medium	Low	None	Low	Very high
Fossil & Nuclear	Medium RES but high nuclear and CCS deployment	Very high	Very high	Very high	Low	Medium

5.2.4.2. System

The clustered European grid model of e-Highway2050 has 103 onshore and 11 offshore nodes, using HVAC and point-to-point HVDC transmission lines. Figure 5.3 presents the 2030 initial system, including any initial offshore wind farms and their point-to-point connectors.

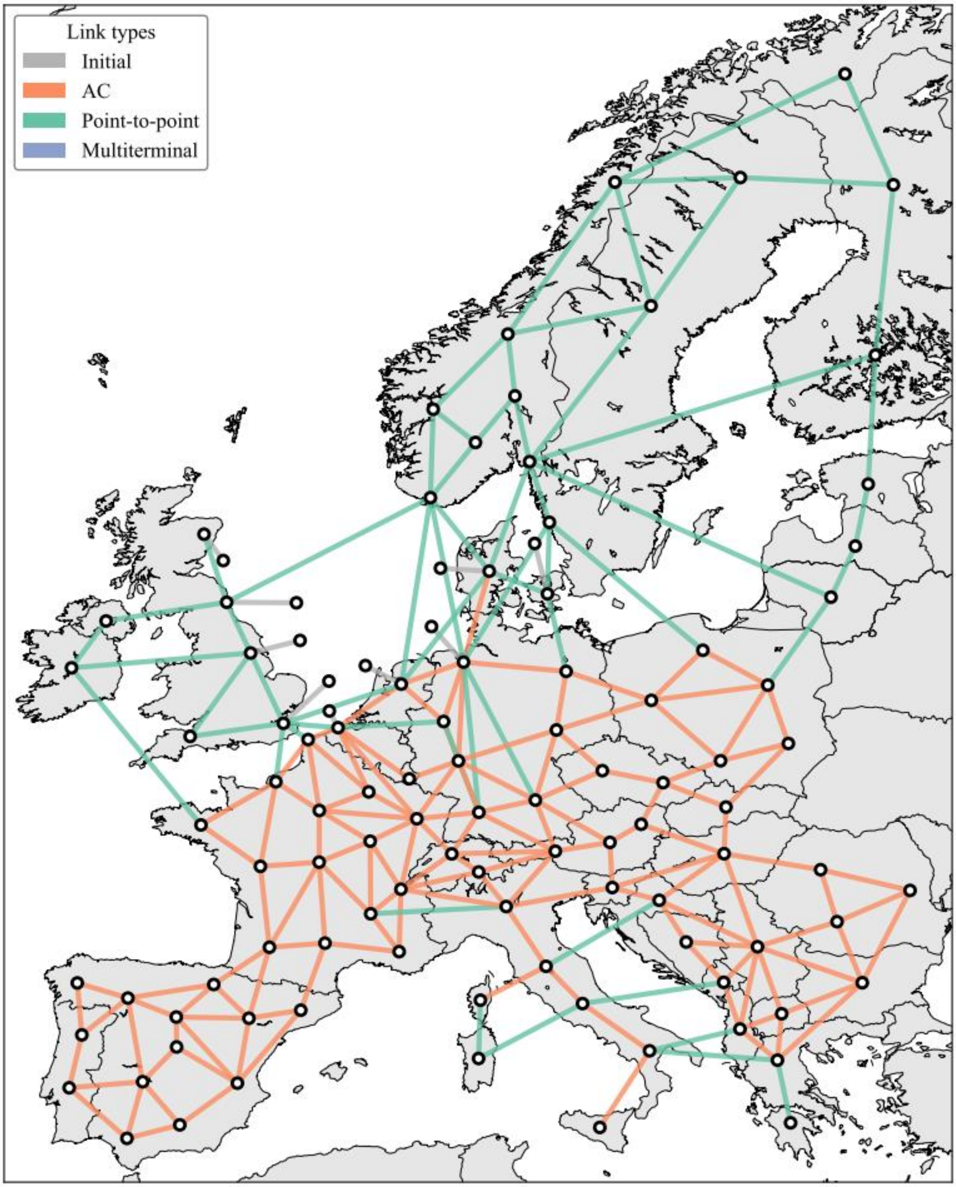

Figure 5.3: 2030 initial system

Table 5.2 presents the assumed component cost and useful lives. Here offshore platform costs are not included, with the consequences for the expansion pathways being briefly discussed in the chapter conclusions. Thus, throughout this thesis the term 'terminal cost' refers to the costs of the offshore converters.

All investment costs are annuitized, with no asset residual value, and all costs and benefits are discounted to 2030 using a 4% discount rate[a]. The total net benefits of the offshore generation and transmission expansion is thus computed as the welfare gains from the expansion when compared to a no-expansion case, minus the offshore wind and transmission investment costs, for all expansion periods, up to the lifetime of the assets.

The storage technologies are concentrated solar power and pumped hydropower storage. The first has an energy inflow from solar radiation, while the latter has no hydropower inflow but may store energy with a round-trip efficiency of 75% as in the e-Highway2050 project.

Assumptions were required, partly due to data availability restrictions. First, exact impedances for onshore lines are distributed in the impedance ranges indicated by the e-Highway2050 project (inversely to line capacities), since exact values are unavailable. Second, differently from the e-Highway2050 project, the offshore wind farm potential (increasing linearly from 2030 to 2050) and starting installed capacity is the same for all scenarios. A higher offshore wind starting capacity and potential are analyzed in the sensitivity analysis. Third, load curtailment for inelastic demand is modelled using a long run value of loss load of 1500 €/MWh [232]. This is lower than the e-Highway2050 value but more adequate for long-term expansion planning. Fourth, marginal costs for generators in 2030 were derived from parameters of the ENTSO-E [233]. Finally, the onshore Nordic and British Isles transmission grid uses point-to-point HVDC lines, as in the data available from the e-Highway2050 project. Hence, some HVAC connections are allowed to the UK, but which do not interact with any British HVAC network.

Table 5.2: Component cost and lifetime data

Component		CAPEX		CAPEX reference	OPEX	Lifetime (years)
Offshore wind farm	Nearshore	1800000.0	€/MW	[234]	2 % of CAPEX [28]	25
	Farshore	2200000.0	€/MW			
HVDC multiterminal cable		1765.7	€/MW·km	[235]		40
AC/DC converter		123000.0	€/MW			
HVAC cable		2895.6	€/MW·km			
HVDC breaker		16666.7	€/MW	[42]		

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[a] This is the rate adopted in the ENTSO-E [230] cost benefit analysis methodology and on multiple European Commission guidelines. It is also within the range recommended in the discount rate analysis of Hermelink and de Jager [231].

The e-Highway2050 node locations minimize the distance between the network clusters. Hence, the location of onshore nodes bordering the North Sea would penalize investments in offshore transmission, due to increased cable lengths. Therefore those clusters are relocated to nearby coastal substations identified in the ENTSO-E transmission system map [236]. This does not affect the onshore system operation and there are no endogenous onshore transmission investments.

The model focuses on the long-term expansion planning of generation, and thus some short-term aspects of power systems are not addressed. These include especially unit commitment constraints, intra-day and balancing markets, and renewable generation forecast errors. These are important aspects for the operation pillar of an offshore grid governance framework [237], but impact less the planning and cost and benefit distribution governance pillars.

5.2.5. Verification

To ensure that the 'that the computer program of the computerized model and its implementation are correct' [212] the results were compared with the e-Highway2050 project, and extreme input testing was conducted.

The largest differences to the e-Highway2050 project are lower generation from biomass (due to a high marginal cost) and higher generation from nuclear (driving down biomass and fossil-based generation) in some scenarios. However, generally generation and load shedding levels of the results are consistent with the e-Highway2050 results, with the assumptions detailed in section 5.2.4 explaining the differences.

Finally, for the extreme input testing null and extreme values are applied for generation installed capacities, and transmission and generation investment and operational costs. Energy constraints and storage round-trip losses are also removed. This allows to observe if the model behaves accordingly, and which extreme inputs affect results the most. For example, generally extreme costs have the largest effect: null investment cost values for transmission or generation may double the net benefits and lead to investments orders of magnitude higher than normal. Also, very high generation marginal costs (equal to the value of loss load) lead to large negative net benefits (more than a hundredfold original positive net benefits). It also eliminates all producer surplus due to the marginal cost homogeneity.

5.2.6. Validation

To ensure that 'within its domain of applicability [the model] possesses a satisfactory range of accuracy consistent with the intended application' [212] the results are compared to the e-Highway2050 project. While transmission expansion in the e-Highway2050 project happens primarily onshore, OGEM focuses on offshore expansion. Thus, increased levels of offshore expansion are observed, especially in the corridor to Britain and Denmark, while corridors to Norway are underinvested. With integration constraints this underinvestment in Nordic corridors is not as pronounced. This could indicate that the integrated lines and co-investment in generation and transmission of OGEM provides greater opportunity for shorter, integrated connections, which negatively affect investments in long Nordic interconnections.

Since the offshore wind potentials of the input data are higher than in the e-Highway2050 project, OGEM results in higher offshore wind installed capacities for all scenarios except the 100% RES. Again, the larger offshore portfolio (including integrated lines), the consideration of multiple transmission technologies and the co-expansion of generation and transmission make offshore wind expansion more attractive, and more in line with current developments. For example, the original Small & Local scenario forecasted a 14.9 GW offshore wind installed capacity, while the North Sea already has almost 10 GW installed and 20 GW consented [11].

These observations corroborate the adequacy of the approach to address the impacts of integrated governance constraints on the North Sea offshore grid expansion, providing more insights for the region than the e-Highway2050 project.

5.3. Results

The left side of Figure 5.4 presents observations regarding the unconstrained offshore expansion pathways, that is, without any active integrated governance constraint. The effect of the integrated governance constraints is indicated on the right, with each line of the figure discussed in detail in the following subsections. Full indicators and the expansion pathways can be found in the appendix B.

Section	**In unconstrained expansion pathways . . .**		**. . . and integrated governance constraints . . .**
5.3.1	Scenarios strongly determine offshore expansion and welfare gains	⇨	Lead to limited welfare losses in absolute terms Affect specific transmission corridors unevenly
5.3.2	There is a high welfare distribution asymmetry for actor groups and countries	⇨	May bring limited benefits to certain countries at the cost of European welfare Affect little the welfare distribution symmetry for actor groups and countries
5.3.3	Line types and technologies strongly affect each other	⇨	Reduce the participation of integrated lines and multiterminal HVDC Increase the effect of path dependence on multiterminal HVDC

Figure 5.4: Effect of integrated governance constraints

In unconstrained expansion pathways scenarios strongly determine offshore expansion and welfare gains. Then, as discussed in section 5.3.1, the integrated governance constraints lead to limited welfare losses in absolute terms. Moreover, the constraints affect the specific transmission corridors unevenly, that is, they impact the transmission corridor technologies and types differently.

5.3.1. Scenarios determine offshore expansion and welfare gains

The first observation on the unconstrained expansion pathways concerns the central role of differences between scenarios as drivers of offshore expansion and its associated welfare gains, especially the load levels and the cost and capacity of generation. The Fossil & Nuclear and Small & Local scenarios have the cheapest and largest capacity margins (i.e. the gap between average available generation capacity and load), leading to lower needs for offshore investments.

On the other hand, the 100% RES scenario has a particularly tight and expensive margin, leading to higher investments levels and higher load shedding. This low margin is visible in Figure 5.5, which presents the cumulative capacity contribution of each generation technology prior to any offshore wind investment, together with the onshore load (median and 80% interval in grey). Here the average available capacity is slightly above 600 GW and is not even sufficient to meet the 80% percentile load. This indicates significant load shedding would happen in the absence of further offshore wind investments. In the Fossil & Nuclear scenario, on the other hand, the average available generation capacity reaches almost 900 GW and can easily deal with the 80% percentile load level.

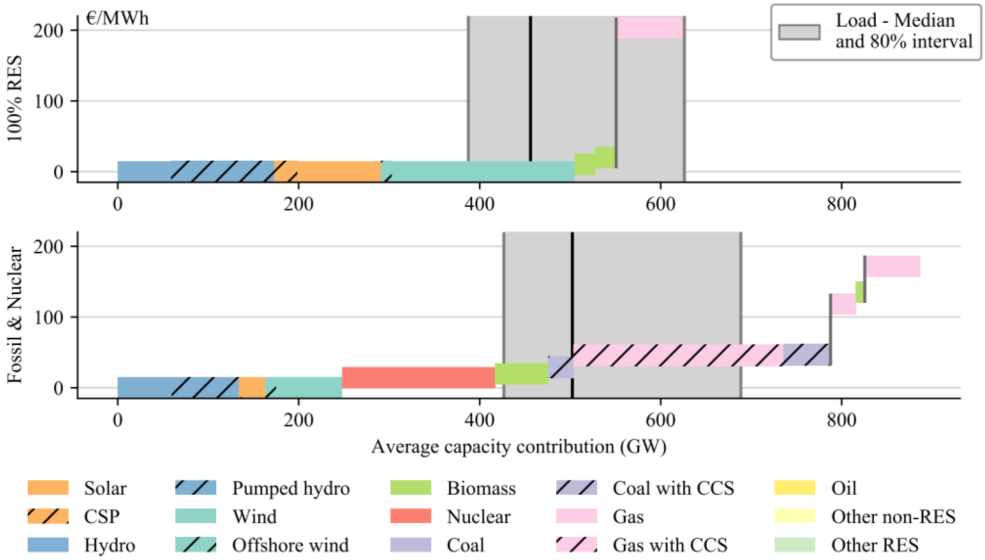


Figure 5.5: 2050 merit order curves without offshore wind investments

Thus, reserve margins strongly determine the general level of investments in offshore transmission and generation. For all scenarios and governance constraints, the initial offshore wind capacity in 2030 is 25.3 GW, in line with the 2016 European Commission reference scenario [238]. Endogenous investments in offshore wind lead to total installed capacities between 51.4 and the maximum potential of 114.9 GW in 2050 for the unconstrained case (up to 172 B€$_{2030}$ in investments). The highest deployment levels are observed in the 100% and Large-scale RES scenarios. By 2050 offshore wind and transmission investments lead to low nodal prices (below 60 €/MWh) in most of Europe. Total transmission investments range from 6.5 to 24.0 TW·km for the unconstrained case (up to 55.7 $B€_{2030}$ in investments). This represents an addition by 2050 of up to 11 % in TW·km to the 2030 grids of the e-Highway2050 project.

Reserve margins between scenarios also determine the welfare gains of expansions. The 100% RES presents the highest net benefits (24.4 B€/year for 226.4 B€ in investments) and the Fossil & Nuclear the lowest (1.5 B€/year for 77.8 B€ in investments). This is in line with the corresponding generation reserve margins and costs. As a comparison, the estimate of the 2016 North Sea regional planning of the ENTSO-E [16] for the offshore grid benefits reach 2.6 B€/year for 24.8 B€ in investments. However, this estimate covers only 2030 and just transmission expansion, while here three expansion periods are considered including generation expansion, and thus welfare gains are logically higher.

The low-benefit scenarios assume the availability of low-cost nuclear and fossil-based generation with carbon capture and storage, or low demand levels. Thus, there are large benefits in deploying offshore wind and transmission given tighter and more expensive generation capacity driven by a lack of carbon capture and storage, which seems the more probable future.

Finally, common national reserve margins across scenarios lead to some common transmission corridors, namely Germany-Denmark and three corridors from Great Britain to France, Belgium and Netherlands (Appendix B). In the 100% RES scenario they are driven by insufficient generation in continental Europe, while for the other scenarios the continental merit order curve is more expensive than in the British Isles and Scandinavia. A Norway/Sweden corridor to continental Europe is not common to all scenarios because in the nuclear- and fossil fuel-based scenarios the Scandinavian capacities are much smaller.

Constraints lead to limited welfare losses in absolute terms and affect specific transmission corridors unevenly

While scenarios strongly determine the welfare gains of the unconstrained offshore expansions, integrated governance constraints reduce these regardless of the scenario. Thus, the complex cooperation, disintegrated planning and Pareto constraints may represent welfare losses of 15% or more, but in absolute terms remain limited to under 0.5 B€/year for all scenarios and constraints.

Moreover, integrated governance constraints do not necessarily have a negative impact on offshore generation or transmission investment levels, although the same cannot be said for specific line types or technologies, as discussed in section 5.3.3. Offshore investments can be independent from generation investments when subsequent periods leverage the pre-existing offshore system, expanding offshore wind or transmission capacity separately. Nonetheless, this decoupling is limited: usually the scenario characteristics drive both the expansion of offshore transmission and of generation. Thus, the ratio of transmission and generation investments is stable across scenarios, with or without constraints.

Concerning common transmission corridors across scenarios, the complex planning constraint maintains more similar levels of investment. The effect of the Pareto constraint is mixed, sometimes building the integrated lines of the common transmission corridors, but often not. Then, there is no investment in the Germany-Denmark corridor under the disintegrated planning, while Great Britain-Netherlands sees its capacity generally reduced. The effect of each constraint is directly related to the participation of integrated lines in these corridors. Hence rather than substituting prohibited integrated lines for conventional ones, the constraints may shift the expansion to conventional domestic wind connections.

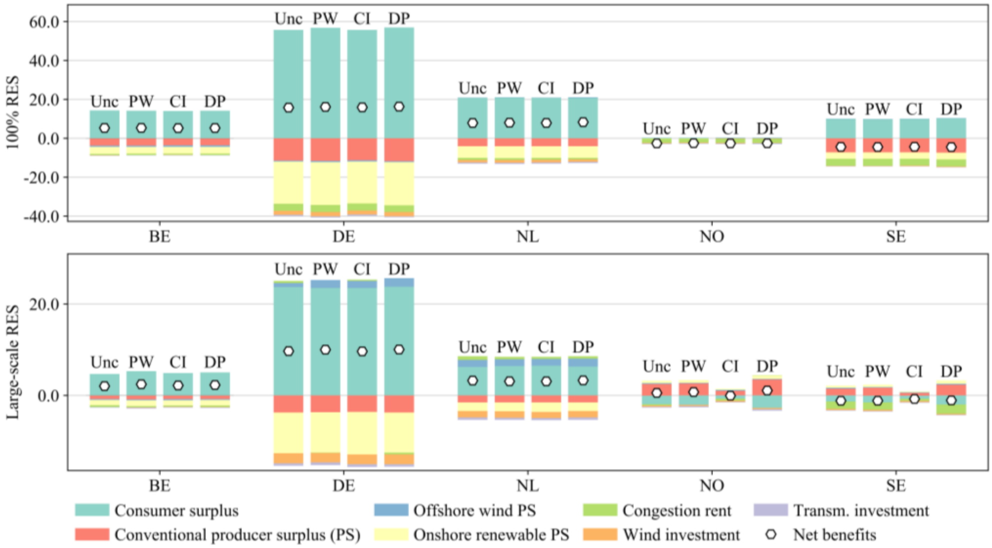
5.3.2. High welfare distribution asymmetry for actors and countries

In unconstrained expansion pathways the distribution of costs and benefits per actor and country is strongly asymmetric, a common feature of power systems – see for example Pudjianto et al. [239]. Then, as detailed in section 5.3.2, the integrated governance constraints may bring limited benefits to certain countries at the cost of European welfare. Moreover, the constraints affect little the welfare distribution symmetry for actor groups and countries.

Regarding the distribution of total costs and benefits, Appendix B presents the data for all actors, countries and scenarios. The 100% RES and Large-scale RES scenarios present the largest costs and benefits per actor and country in accordance with their higher European investment levels.

Generally, the largest and most stable net benefits occur to Belgium, Germany and the Netherlands, reaching up to 16 B€/year for Germany (8% of its operational cost in 2050). Consumer surpluses arising from price reductions are the main contributor, and can be traced back to an increasing offshore wind and transmission capacity (Figure 5.6). On the other hand, generally Norway and Sweden lose out due to negative surpluses for their hydro producers caused by price reductions, though usually net losses are small. Since in the unconstrained pathways these countries cannot constrain the transmission expansion, they still cooperate to develop integrated lines, despite their losses.

A major winner from offshore investment are offshore wind producers themselves, who exhibit significant surpluses in all high-investment scenarios. Nonetheless, since investments are optimized at the system level, at country level surpluses may not be sufficient to cover investment costs. Also, pre-existing offshore wind may lose due to price reductions from subsequent investments. Finally, onshore intermittent renewables producers generally lose with the introduction of offshore wind due to price decreases, just as conventional onshore generators. This is more pronounced for onshore wind than solar PV generators, due to the higher availability correlation with offshore wind and to a lesser scale to the higher onshore wind installed capacity.



Constraints: Unc - unconstrained; PW - Pareto welfare;
CI - complex integration; DP - disintegrated planning

Figure 5.6: Selected annualized costs and benefits (B€/year)

Constraints may bring limited benefits to certain countries at the cost of European welfare losses and affect little the welfare distribution symmetry for actor groups and countries

The literature indicates that the asymmetric distribution of costs and benefits is a central barrier to the development of an integrated offshore grid. The study confirms this by studying the effect of the integrated governance constraints on line types and technologies, as discussed in section 5.3.3.

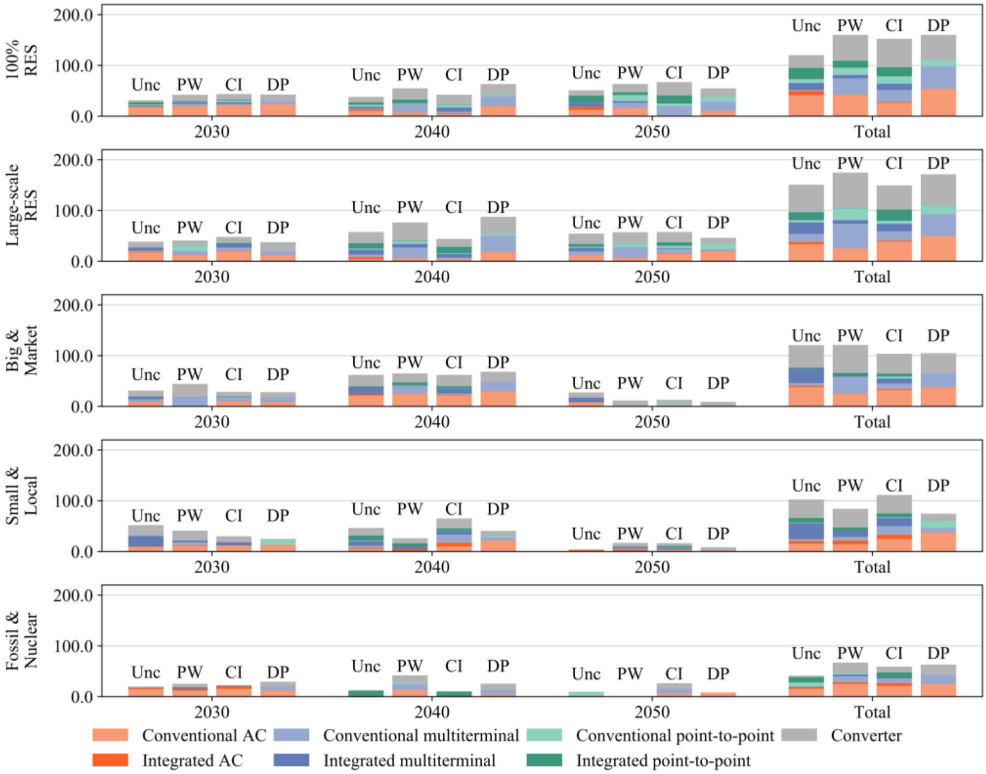
But the impact of the integrated governance constraints on the welfare of individual countries is small. When countries do not cooperate in welfare-reducing periods with the Pareto constraint, this only leads to a slight reduction in losses for them (and consequently for national actor groups). Thus, the capacity of countries to limit their losses by not cooperating is limited. Individual countries can cause welfare losses to Europe which are not compensated by their individual gains.

Hence, the effect of the constraints is stronger regarding the effect on the deployment of specific transmission corridors, types and technologies, as discussed in the sections 5.3.1 and 5.3.3. Also, the effect on the profitability of individual offshore transmission and wind farm assets deserves further attention.

5.3.3. Line types and technologies strongly affect each other

In the unconstrained expansion pathways there is a strong interaction between the line types (conventional or integrated) and the three transmission technologies: HVAC and point-to-point and multiterminal HVDC. As detailed in this section, the integrated governance constraints on their turn reduce the participation of integrated lines and multiterminal HVDC. They also increase the effect of path dependence on multiterminal HVDC.

First, the analysis for the unconstrained expansion pathways is presented. Figure 5.7 presents the resulting transmission expansion capacity classified by technology. In the high-investment Large-scale RES scenario, multiterminal HVDC lines are the main technology, accounting for over 48% of the total TW·km. Multiterminal HVDC can form regional multiterminal grids but also local ones, involving only some North Sea countries, such as the French-Dutch grid of Figure 5.8. The path dependence identified in Dedecca et al. [21] leads to the reinforcement of pre-existing multiterminal grids, through new investments in multiterminal HVDC lines and/or converters. An example is Scandinavia in the unconstrained Large-scale RES case, which invests in HVDC converters in 2050 without any significant new multiterminal HVDC lines.



Constraints: Unc - unconstrained; PW - Pareto welfare;
CI - complex integration; DP - disintegrated planning

Figure 5.7: Results for transmission capacity expansion pathways (GW)

Point-to-point HVDC remains an important technology, especially in high-investment scenarios, where it can provide an exclusive connection between two nodes, most often through integrated lines. Hence, it is central to the 100% RES scenario, even in the 2040 and 2050 periods, partly crowding-out multiterminal investments.

HVAC is the least used technology for scenarios with large investments, especially due to its length limitation to 200 km, which restricts the candidate portfolio almost exclusively to conventional lines. However, it is the technology of choice for early projects and its investment levels are more stable, which is coherent with it being more attractive for near-to-shore projects. On the other hand, a more strict and realistic limit such as 100 km would lead to a few HVAC lines not being deployed.

Regardless of integrated governance constraints, there are significant intra-country transmission capacity investments, especially in Germany, Denmark, Great Britain and the Netherlands, which have the highest offshore development. While cross-border transmission corridors make extensive use of integrated HVDC lines, intra-country connections often leverage HVAC lines. In this way, there can be a complementarity of technologies and line types. For example, in 2030 the conventional HVAC connection of the German wind farm complements an integrated line to Denmark (Figure 5.8). In this way, the offshore wind expansion, national merit order curves and loads interact with the integrated offshore grid expansion. Low or expensive generation capacity margins drive offshore wind development and specific transmission corridors, while the offshore node locations influence integrated lines. Finally, the offshore grid can combine technologies to avoid HVAC and multiterminal HVDC loops and consequently the load flow constraints of equations (5.3-5.6). Thus, complementary transmission technologies can eliminate single-technology loops in grids.

Since OGEM does not model the expansion of storage technologies, the interaction of transmission and storage expansion such as in Bustos et al. [227] is not analyzed. The possible expansion of storage technologies could significantly alter the main transmission corridors by increasing the importance of Scandinavian hydropower storage or by other factors.

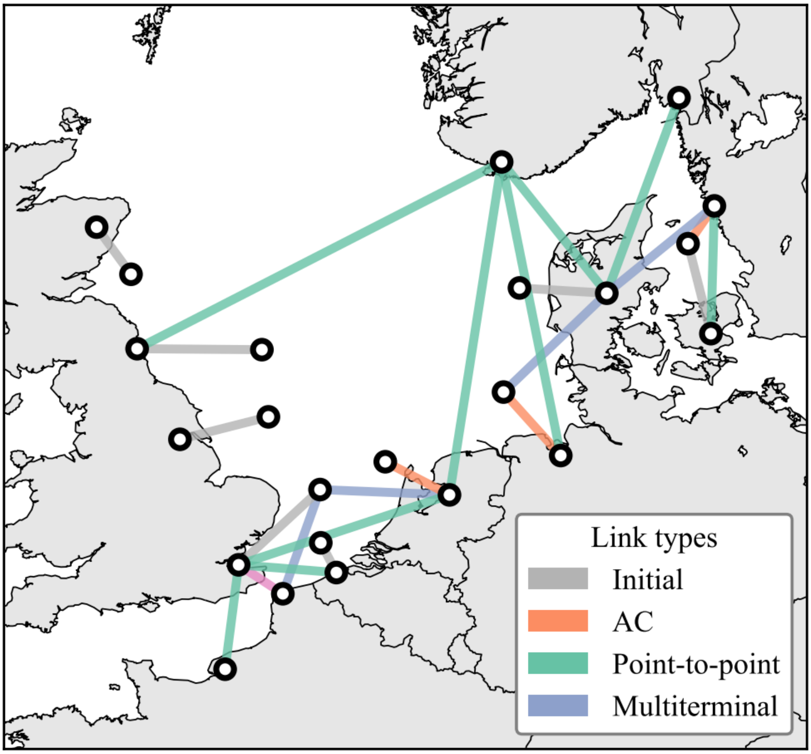


Figure 5.8: Unconstrained Large-scale RES scenario grid in 2030

Constraints reduce the participation of integrated lines and multiterminal HVDC, and increase the effect of path dependence on the latter

The ability of each constraint to build multiple, separate or no integrated lines affects more the multiterminal than the point-to-point HVDC. This is sensible since the potential benefits of multiterminal HVDC are greater when it is possible to build multiple integrated lines simultaneously. In low investment scenarios, the share of HVAC increases as investment in integrated lines decreases, accompanying the reduction in investments in integrated cross-border transmission corridors. In high-investment scenarios the capacity of HVAC remains constant, for then there is significant investment in cross-border corridors, albeit different ones than under the unconstrained case. Nonetheless, the transmission technologies keep their observed complementarity under any governance constraint.

Moreover, path dependence influences the deployment of transmission technologies, as further similar investments in a technology are more likely after its initial deployment. For example, after a certain transmission corridor uses multiterminal HVDC or a complementary technology to avoid transmission loops.

The disintegrated planning constraint blocks any kind of integrated grid. This partially shifts investments from wind farms located closer to load centers to eastern wind farms. Accompanying this, central nodes of the unconstrained multiterminal grids shift from offshore to onshore ones, especially in Denmark. Thus, the disintegrated planning constraint does not impede multiterminal grids but changes the interaction of offshore wind and transmission expansion significantly.

The complex integration constraint is more subtle, reducing the participation of integrated lines (Figure 5.7). Furthermore, although by 2050 there are multiple integrated lines per offshore node in high-investment scenarios, these lines are added sequentially, one per investment period. For example, in the Large-scale RES scenario, by 2040 complex planning still develops multiterminal grids. These are however focused on onshore nodes and leveraging multiterminal line investments made in 2030 (Figure 5.9).

The Pareto welfare constraint has a similar effect as the disintegrated planning constraint, significantly reducing investments in integrated lines, despite not explicitly blocking them. In high-investment scenarios this actually leads to higher transmission investment costs despite stable investment levels in offshore wind, and possibly higher investment in conventional multiterminal HVDC lines. However, the number of lines built is higher than in the former constraint, which indicates a lower line average capacity.

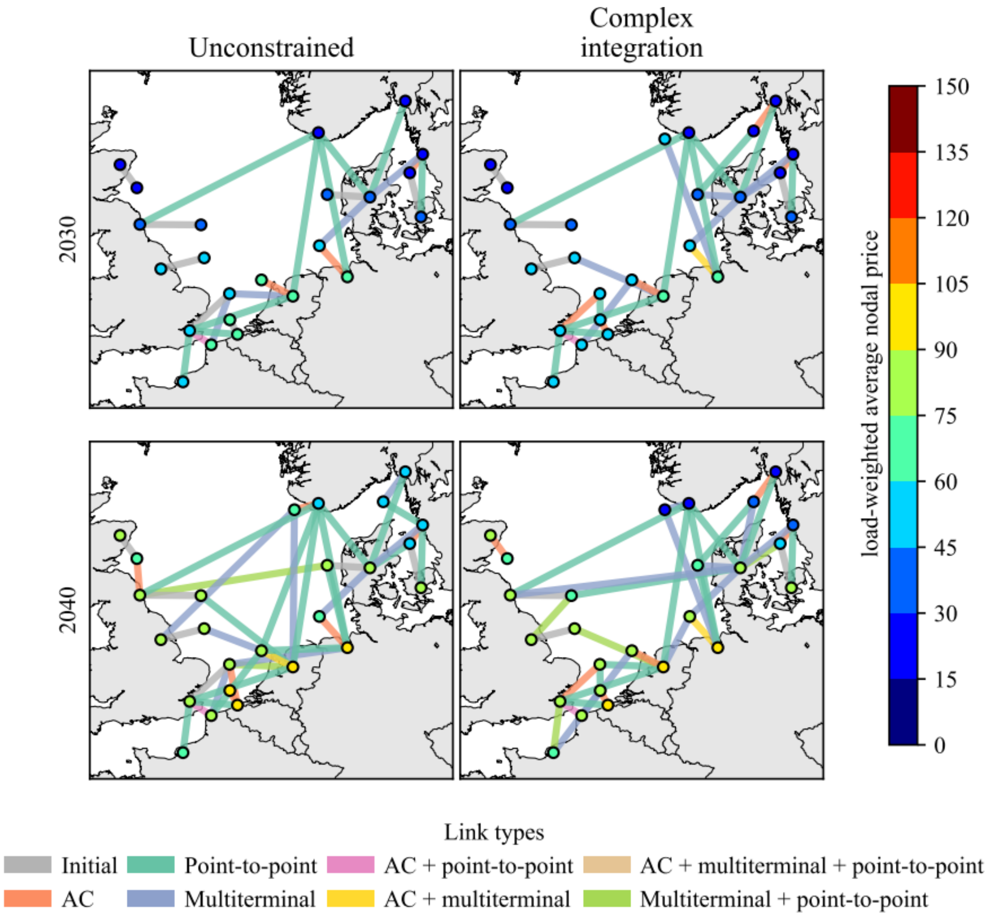


Figure 5.9: Multiterminal HVDC expansions in the Large-scale RES scenario

5.3.4. Sensitivity analysis

In order to further understand the impact of uncertainties and modeling assumptions on results the sensitivity analyses indicated in Table 5.3 are conducted.

Across, scenarios, decreases of 25% in investment costs for HVDC cables lead to increases of multiterminal and point-to-point HVDC investments of up to 52% in TW·km. Cost increases in their turn favor HVAC cables at the expense of point-to-point investments. Cheaper DC converters favor both HVDC technologies, while cost increases affect mainly point-to-point HVDC. The inclusion of DC breaker costs favors point-to-point HVDC at the expense of multiterminal HVDC, for only the latter requires them, though a more detailed technological representation would nuance these results. Finally, a 25% offshore wind investment cost increase affects HVAC transmission the most, with a 34% reduction in TW·km investments.

These trends vary per scenario however, and there is no direct relationship between absolute investments in a certain transmission technology per scenario and the influence of investment cost changes. This lack of a clear relationship is compounded by the fact that the relative attractiveness of each transmission option may be more important than the absolute investment cost for any single technology. Thus, counterintuitively, investment cost increases which affect both HVDC technologies may lead to higher investments in one of them. This reinforces the conclusions of Dedecca et al. [21] regarding the importance of considering the relative cost and performance of the different transmission technologies.

Table 5.3: Sensitivity analyses

Sensitivity		**Parameter values**	**Justification**	**Data source**
Offshore wind capacity and potential	Initial capacity	80.0 GW	Favorable cost reduction and deployment forecasts [11]	[16] [240]
	Potential	147.3 GW in 2030 355.0 GW in 2050		
Transmission investment costs	HVDC cables	1324.3-2207.1 €/MW·km	Costs uncertainties [200,241].	[235]
	HVDC converters	92.3 to 153.8 M€/MW		
Offshore wind CAPEX	Near-to-shore	1350.0-2250.0 k€/MW	Values of e-Highway2050 compared to IRENA [242]	[234]
	Far-to-shore	1650.0-2750.0 k€/MW		
HVDC circuit breakers	Investment cost	16.7 k€/MW	Uncertainty in requirements and cost	[42]
Hydropower energy availability	Hydropower inflow	+/- 25%	Analyze impact of wet and dry years	-
Discount rate		0-9%	Representation of social and private perspectives	[231]
Time series		Alternative realization for wind, solar and load	Impact of specific time series given deterministic approach	e-Highway2050 project

Increases or decreases in hydropower energy availability inversely affect offshore wind investments and directly affect the interconnection of Scandinavia with continental Europe, at the expense of interconnection to Great Britain. Thus, these changes affect the main offshore transmission corridors, but do not have a clear effect on the general level of transmission investment nor in the chosen transmission technologies.

A higher offshore wind potential leads to significantly more investments in offshore wind for the 100% RES and Big & Market scenarios, with a final 2050 installed capacity of 178.5 and 151.4 GW respectively. On the other hand, the higher starting installed capacity means that generation investments for the Small & Local scenario are actually lower, and remain stable for the remaining scenarios.

Thus, given adequate scenario characteristics with tight and/or expensive onshore capacity margins, higher offshore wind potentials can be very beneficial.

Discount rate changes affect especially the low-investment scenarios, while investment in the 100% and Large-scale RES scenarios are affected, but not as significantly. This indicates that the tight and expensive capacity margins of the latter scenarios are still determinant drivers for the offshore expansion despite the change in benefits provided (which are inversely proportional to the discount rate changes). Regarding the technologies, the stability of HVAC transmission to different investment levels already noted in section 5.3.3 remains, while HVDC transmission technologies accompany the increase or decrease in investment brought by the discount rates. Also, there is no evidence that discount rate changes particularly affect the deployment of integrated lines.

Finally, the main impact of an alternative offshore wind time series is an increased multiterminal HVDC deployment in the high-offshore wind scenarios due to path dependence. Thus, a slightly higher investment in the technology in 2040 leads to significant further deployment in 2050. This indicates that path dependence can lead to significant differences in the offshore expansion pathway. This does not alter the exploratory model conclusions on the interaction of technology and topology, nor the principles for offshore governance frameworks. In this way the sensitivity analyzes reinforce the importance of the interaction of transmission technologies, of generation and transmission expansion and the path dependence of offshore expansion.

5.4. Conclusions

Using a myopic model, the impact of integrated governance constraints on the offshore generation and transmission expansion pathways was analyzed. *The novel Pareto welfare and integration constraints represent governance endogenously*, a growing necessity given the importance of the governance decision-making approach in expansion planning. This allows OGEM to address the third subordinate research question, of the effect of these barriers on offshore expansion pathways.

The offshore grid expansion benefits are positive but highly dependent on the scenarios and asymmetrically distributed between countries and actor groups, and governance constraints affect benefits negatively: up to 0.5 B€/year can be forfeited. The e-Highway2050 scenarios succeeds in representing very different futures, but given offshore wind cost reductions and the current difficulties faced by nuclear and carbon capture and storage technologies, the high-renewables, high-investment scenarios (where benefit losses from constraints are highest) seem more probable.

However, the novelty of the integrated governance constraints lies in more subtle insights. *Constraints limit integrated lines and thus influence the expansion pathways through different channels.* First, in the Pareto constraint, losing countries do not cooperate, despite the potential to reduce their own losses at the cost of increasing societal ones being limited. Second, the complex cooperation complicates the expansion planning by enhancing path dependence and thus demanding anticipatory measures and/or intertemporal coordination between expansion periods. Finally, the more traditional disintegrated planning constraint restricts but does not impede the deployment of multiterminal HVDC transmission, where the ability to build multiple integrated lines simultaneously is important.

Also, *important offshore corridors are determined by scenario differences in generation reserve margins between countries.* While corridors which leverage integrated lines are significantly affected by the governance constraints, conventional corridors may remain untouched. Thus, instead of replacing integrated for conventional lines, a governance constraint may shift transmission to completely different corridors. On the other hand, *governance constraints have little effect on the net benefits distribution asymmetry* observed.

Although a top-down decision-making paradigm is not adequate for Europe, *there is currently no proven governance framework for expansion planning*, especially for the offshore grid. *The chapter results do confirm the importance of the design principles of Dedecca et al.* [21] for a governance framework. First, expansion planning must consider all combinations of technologies and candidate lines, or risk forfeiting economic, environmental and operational benefits. Second, intertemporal considerations are pivotal to address path dependence and lock-in. Third, the interaction of technologies must be considered, as well as technological innovation, which will change the relative attractiveness of each technology.

To these principles, a fourth can be added: *the deployment of multiterminal HVDC and of integrated lines are partly independent.* Hence, a governance framework must be capable to address the compatibilization and planning of multiterminal grids separately of the deployment of integrated lines. Nonetheless, a disintegrated grid leveraging multiterminal HVDC is a second-best solution - Europe should strive for an integrated offshore grid, with a corresponding governance framework.

The version of OGEM in this chapter includes generation expansion, uses a more detailed case study, and reduces the optimization heuristics in comparison to chapter 4. This provides for *more detailed expansion pathways which allow for more insights* regarding welfare gains and distribution from the offshore expansions as well as regarding the interaction of line types and technologies. On the other hand, *the simpler case study of chapter 4 and the optimization heuristics allows to study some investment management factors which were not addressed in the present chapter.* For example, the ratio cost and benefit indicator of equation (4.2) could not be implemented in a linear optimization problem. However, the number of expansion candidates in the portfolio is inherently limited. Thus, the OGEM version of this chapter is more suited to consider the complex interaction of generation and transmission expansion and line types and technologies. Also, any offshore node can act as an offshore hub in chapter 5, while in the case study of chapter 4 only one node acts as such.

Nonetheless, the *OGEM versions of chapters 4 and 5 share common characteristics* which are central to studying the effect of governance constraints and the investment management factors of the offshore grid. First, both consider linearized transmission load flow constraints, which lead the expansion problem to often avoid transmission loops by combining transmission technologies or choosing alternative corridors. Second, both versions consider multiple transmission technologies, which strongly interact with the line types. Third, the consideration of multiple expansion periods indicates that path dependence plays a strong role in the offshore grid expansion. Fourth, both chapters 4 and 5 indicate that offshore generation and transmission expansion are strongly correlated, regardless of whether generation is modelled endogenously or not.

Lastly, *one of the core tenets of OGEM is its exploratory approach* aiming at studying the investment management factors and refraining from a normative approach prescribing actual expansion plans. *All energy system modeling approaches must to some level be careful with prescribing actual expansion plans.* For example, choosing a limit lower than 200 km for HVAC lines in OGEM could lead to different expansion plans. However, the solution space flatness common to generation and transmission expansion planning problems in general makes the exploratory approach of OGEM all the more relevant.

Another important *caveat* to the expansion pathways resultant of OGEM is the consideration of offshore platform costs (whether for HVAC or HVDC). As these represent significant costs and may exceed those of converters, they can alter significantly the expansion pathways. This could increase the attractiveness of integrated expansions using multiterminal HVDC, which have the potential to reduce the number of platforms and their capacity.

6 Regional offshore governance and the Energy Union[a]

6.1. Introduction

Chapters 3 to 5 addressed the second and third subordinate research questions. They focused on the contributions of modeling to understanding the influence of governance barriers to expansion pathways of the integrated offshore grid. However, as alternative modeling approaches can provide complementary insights into these pathways, so qualitative methods can complement models of the offshore grid.

Hence, this chapter addresses the fourth subordinate research question: how adequate is the current European expansion governance framework to enable the integrated offshore grid? For this, current challenges for the regional governance of the integrated expansion of the offshore grid are identified. In parallel, to address multiple energy and climate objectives the European Union is implementing the holistic strategy of the Energy Union. Hence, it is also analyzed how the Clean Energy Package (the main regulatory reform of the Energy Union) affects these challenges.

There is currently no analysis of the expansion governance framework for an integrated offshore grid in the North Sea region considering the changes brought by the Clean Energy Package. Also, due to the youth of the Energy Union, the literature on it is mostly non-peer-reviewed [138]. The motivation for the analysis is to allow integrated projects for the offshore grid in the European North Sea to compete with non-integrated transmission and generation projects on an equal footing.

The first contribution of this chapter is highlighting five challenges for a regional governance framework for offshore expansions in the context of the Energy Union, using for that analysis the governance dimensions of level, implementation obligation and implementation discretion. Second, the analysis through governance dimensions developed provides an initial pathway for the analysis of other governance frameworks, a decision-making mode whose relevance is increasing with the unbundling of power sectors worldwide. Third, another contribution is to the understanding of the regional level of governance. Its importance is increasing with the regional interconnection of onshore systems in Europe and the US, and the discussion on other offshore grids in Europe, the United States and Asia [19,73,104].

As indicated, the analysis is structured according to governance dimensions selected from the literature on governance studies. These are the level (European, regional or national), implementation obligation (binding or not binding) and

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[a] This chapter is based on Dedecca et al. [30] with modifications.

implementation discretion (rigid or flexible). The regional level has a particular importance in the analysis, for much of the governance of the offshore grid expansion should take place at this level, in line with recent developments concerning the design of the European expansion framework [24,243]. This is the first application of the three dimensions to structure the analysis of the regional governance of offshore expansions.

Given the objective, some aspects are out of scope of the research. First, developments at the subnational level are not addressed. Second, neither are other Energy Union dimensions such as energy efficiency or Energy Union changes related to power distribution and prosumers. Finally, the integration of the offshore power sector with other marine sectors in the context of ecosystem-based marine management is not discussed [244,245].

Figure 6.1 presents the structure of the analysis of regional governance of offshore expansion in the North Seas. The rest of this chapter is structured as follows. In the remainder of section 6.1 the concept of regional cooperation is presented, since the other key concepts of the offshore grid and the Energy Union are presented in chapter 2. Section 6.2 presents the methodology, where governance dimensions are selected to conduct an analysis of the offshore expansion governance challenges identified in a literature review. Then, section 6.3 presents the results: first a short summary of the challenges, and then their detailed analysis. Finally, in section 6.4 overarching conclusions from the identified challenges are drawn.

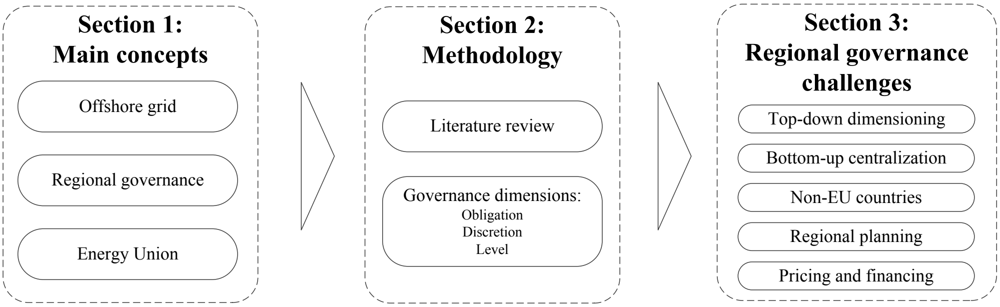

Figure 6.1: Analysis structure of the regional governance

6.1.1. Regional cooperation

Paraphrasing the European Commission [246], a region is defined as

> an area including territory from a number of different countries . . . associated with one or more common features or challenges.

As such, regions are a fluid concept combining both territorial and functional aspects [247]. Cooperation for decision-making at the regional level has a number of advantages over that at the European or national ones. Regions are the natural level for ‘problems that one country is unable to tackle alone, or which spill over international boundaries while being too specific in scope to be addressed by general EU rules' (Danson, 2017). It groups all actors necessary for decision-making while excluding actors not necessary and/or not impacted by the issue at hand. This facilitates the decision-making and implementation of the solutions [248], while not causing externalities beyond the region boundaries. Also, regions allow to account for heterogeneous national specificities [249] while European solutions may not. Moreover, regional decision-making may have synergies with decision-making at other levels, filling authority gaps [97]. Hence, regional initiatives are more feasible and adequate to fostering energy policy cooperation in Europe [24,135,243].

On the other hand, regional decision-making has a number of disadvantages. These include the possibilities of failing to reach targets, free-riding, leakage (such as of carbon emissions), a higher potential for inconsistent and even balkanized policies, and monitoring failures [93,145]. Also, the interest of national actors may block decision-making at the regional level [248,250].

The North Sea offshore grid has a number of specific characteristics as seen in section 2.2, which qualify the region as a valid level for decision-making. This even more so considering the significant externalities (both positive and negative) a North Sea country can impose on another, and the increased benefits of an integrated grid compared to a conventional, non-integrated one as demonstrated in chapters 4 and 5.

The first characteristic is the importance HVDC technology has for the grid, since a multiterminal HVDC leveraging voltage-source converters will be a significant component of an integrated offshore grid. Second, the offshore grid has a greater potential than onshore grids for the integrated expansion of generation and transmission, which does however require greater coordination. Finally, the decentralization of the offshore grid (such as the multiplicity of actors and countries) also requires a stronger coordination of these actors, in a context of regulatory differences between countries which may hinder the development of an integrated grid.

Thus, the North Sea region qualifies as an adequate decision-making level for the offshore grid. However, due to its decentralization this process can only occur through governance. Jay and Toonen [111] already indicate that the regional level is central to the governance of the North Sea offshore grid. This is confirmed by the support to regional initiatives and the North Sea in particular from research and multiple European and national actors [111,145,243,248,251]. Existing regional groups include the North Seas Energy Cooperation and the North Sea regional group of the European Network of Transmission System Operators for Electricity (ENTSO-E), with even a North Sea macro-region being considered [25,250].

In the case of the offshore grid, one may nonetheless question the regional level as the most adequate one for decision-making, as expansions unavoidably affect all parts of the power system. In this way, the offshore grid impacts even remote European countries. However, compared to North Sea countries these impacts will be more limited and infrequent. Moreover, the impact is often positive and affects certain neighboring countries much more than others. For example, the analysis of chapter 5 finds significant positive welfare effects for Spain, Italy and Poland in certain offshore expansion scenarios, while other countries are not impacted. Nieuwenhout and van Hout [58] also find Spain benefits from the integrated offshore grid, even though it would prefer a conventional, non-integrated one.

Moreover, stable regional governance frameworks provide several advantages over ad hoc, project-specific cooperation between North Sea countries. Regional governance avoids the duplication of resources in the case of several specific projects between the same group of countries. Also, it allows cooperation on issues which are not project-specific. For example, the North Seas Energy Cooperation initiative works on issues such as maritime spatial planning, the planning of the integrated offshore grid, standards and technical rules, the alignment of support schemes for offshore wind, and synergies with the offshore oil & gas sector [25].

In this way the advantages of governance at the regional level outweigh the advantages of focusing on European or project-specific cooperation. The interests of neighboring European (and non-European) countries may be taken into consideration through other measures, such as consulting significantly-affected countries, and only at necessary times.

Nonetheless, European policy makers and researchers may still advocate for pan-European or project-specific cooperation, which warrants the assessment of the compatibility of regional governance with these approaches. Although the regional level is central for expansion planning in the North Sea, it is not the only level – the European and national ones will always play a role. Furthermore, regional governance could lead in the future to a unified pan-European governance of integrated offshore expansions. On the other hand, a project-specific approach is more incompatible with a regional one, since the analysis of the individual offshore projects' costs and benefits would not internalize the regional benefits and costs of integrated expansions. Despite this, other considerations such as practicality could argue in favor of pan-European or project-specific governance approaches.

In addition to questions over the adequacy of the regional level, support for the formalization of regional cooperation in the North Sea and in the European energy system in general is only partial [89,105,107,126]. Also, formalization in the form of a North Sea macro-region is unlikely in the medium-term [250]. Moreover, concrete integrated offshore projects are still scarce, and essentially bilateral [111]. The few examples include the Kriegers Flak Combined Grid Solution between Denmark and Germany, and the COBRA interconnector between Denmark and the Netherlands, for which studies were conducted for the possible connection of offshore wind [26,252].

Hence, while regional governance of the North Sea offshore grid for its integrated development is both sensible and desirable, there are a number of challenges to it. These challenges are related also to the main current strategy of the European Union for the European energy and climate policies: the Energy Union, which is discussed in section 2.4.4.

6.2. Methodology

To analyze the European governance to develop an integrated offshore grid under the Clean Energy Package, a methodology in three steps is applied. First, a literature review is done, based on a structured search and further sources familiar to the authors. Second, governance studies allow to identify dimensions for governance frameworks, and select the most adequate ones to classify the institutions and organizations relevant to an integrated offshore grid expansion. Finally, the selected governance dimensions allow to analyze the regional governance challenges for this expansion of the integrated grid.

The analysis and the literature on the Energy Union consider the Clean Energy Package in its original form, as proposed by the European Commission in November 2016. The conclusions comment on the impact of the version of the Clean Energy Package under negotiation by the European Commission, Council and Parliament as of July 2018.

6.2.1. Literature review

To identify the governance challenges a literature review on the Energy Union, regional governance and the offshore grid was conducted, which allowed for the compilation of aspects for these topics. Given the large number of aspects identified, it was necessary to concentrate on a select number. First, the challenges identified had to relate to the integrated offshore grid, since although relevant, other challenges were deemed too general. For example, this applies to the need for improvements in the ENTSO-E cost benefit analysis, as discussed by Bhagwat et al. [114]. Second, the challenges had to relate specifically to the regional level, given the focus of this chapter on regional governance.

The structured search on Google Scholar and Scopus combined the terms of Figure 6.2 to identify peer- and non-peer-reviewed documents on the above-mentioned topics[a]. To this selected literature other sources were added: the Clean

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[a] Each term has multiple alternatives in order to identify all relevant documents. The search was restricted to the English documentation published since 2009, when the 3rd Energy Package entered into force. Documents excluded include those with a different geographical scope than Europe or the North Seas, those focusing Energy Union dimensions not directly related to the research at hand

Energy Package documents from the European Commission [4,148,253,254], any other relevant documents familiar to the authors, and the presentations of recent Electricity (Florence), Energy Infrastructure and North Seas Energy forums.

Topic: Energy Union

Term 1	Term 2
energy union	governance
clean energy package	expansion plan*
clean energy for all Europeans	decision*making
winter package	regional cooperation

Topic: Regional Governance

Term 1	Term 2	Term 3	Term 4
europ*	power	regional	governance
	electricity	north* sea*	expansion plan*

Topic: Offshore Grid

Term 1	Term 2	Term 3	Term 4
north* sea*	offshore	grid	governance
europ*		network	expansion plan*
		infrastructure	

Figure 6.2: Literature search terms

6.2.2. Governance dimensions

One can classify different governance frameworks according to several possible dimensions [96]. Some of the main dimension groups in the literature governance are presented here, in order to select the ones for the regional governance analysis.

Treib et al. [96] develop an extensive categorization of governance according to policy (instruments), politics (actors) and polity (structure). As an example of an analysis structure for policy, the authors categorize legal instruments for governance according to the implementation obligation (binding or non-binding) and the discretion (rigid or flexible). The authors argue that these are the most crucial dimensions for policy instruments in Europe, allowing the analysis of which instruments political organizations use to reach their goals.

Then, Osofsky and Wiseman [97] discuss the dimensions of governance levels (from national to local) and actors involved (public and/or private). They argue for governance structures involving actors from all types and levels, with a focus on

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(such as energy efficiency), and those focusing sub-national regions. * denotes the wildcard for any number of characters.

the interstitial regional level to provide flexibility. The dimensions selected also allow them to analyze the interests of actors and the conflicts which emerged in the specific organizations studied (covering regional structures for citizen participation, grid reliability standards, and transmission expansion).

Börzel [98] analyzes the European Union governance through the dimensions of the actors involved and rule structure (hierarchical, or non-hierarchical of mutual influence or adjustment). In this way the author highlights the primacy of public actors and the layered combination of rule structures, characterized as the 'combination of negotiation and competition in the shadow of hierarchy'. Benz [99] also analyzes the European Union governance, but prefers the dimensions of the coupling degree of elements of the governance framework, and of the interaction direction. The author discusses the adequacy of governance forms to provide decision-making flexibility, avoiding lock-ins or vulnerability to strategic behavior.

Finally, Soma et al. [100] study regional governance for an ecosystem-based management through the dimensions of integration and cooperation. While integration can vary from being fragmented to coordinated at the regional level, cooperation ranges from the confrontation of economic sectors to them working towards deliberative problem solving. The authors conclude that Europe is moving from a fragmented, confrontational marine regional governance to one that is more coordinated and deliberative. Nonetheless, while they see positive developments in cross-sectoral integration, both dimensions exhibit large gaps.

6.2.3. Dimensions for regional governance of offshore expansions

For the European regional governance analysis the dimensions used by Treib et al. [96] are chosen, namely the discretion and obligation dimensions. As seen, the authors indicate that discretion and obligation are crucial to analyze European governance instruments from the policy point of view. This point of view focuses on the policies and their instruments, instead of on actor constellations or the decision-making structures.

However, Treib et al. [96] also state that 'there are probably many hybrid forms of governance modes that combine elements of different dimensions'. Accordingly, to the discretion and obligation the level dimension is added for this analysis, due to the importance of the regional level to the offshore grid, as argued in section 6.1.1. This 'level' governance dimension can be compared to the 'central locus of authority' dimension of Treib et al. [96].

The selected obligation, discretion and level dimensions are briefly discussed here. The obligation to implement regulation depends not only on the legal instruments stating the obligation but also on the existing enforcement instruments. Obligation can range from binding to non-binding, meaning how much the actors have to respect them. Then, the implementation discretion dimension indicates how much freedom actors have in the regulatory details of the implementation, and goes from rigid to flexible. As Treib et al. [96] argues, obligation and discretion are closely related, but the latter indicates how much implementation flexibility exists in the organizations and institutions, i.e. if the implementation rules are very detailed (i.e. rigid) or provide general guidelines (which are thus flexible). Finally, the level dimension covers the level at which the regulations are implemented, comprising the European, regional and national levels.

The main focus of this chapter is to study the current challenges for the regional governance of the integrated expansion of the offshore grid. Additionally, it analyzes how the regulatory reform of the Clean Energy Package affects these challenges. To address these issues, another selection of dimensions would be possible, highlighting different challenges of regional governance and possibly focusing on other aspects of the Clean Energy Package. However, this chapter asserts that the obligation, discretion and level dimensions are the most adequate, compact group for the objectives. The choice of governance dimensions is based on several arguments: the focus on policy and its instruments, as opposed to the actor constellations; the importance of the regional level; and the previous application of these dimensions on governance studies of the Energy Union and other areas.

The selection of level, discretion and obligation governance dimensions has been thus applied explicitly or implicitly to other studies on governance. For example, on the governance of the European 2030 renewable energy targets [145,251], of the European Union [255] or of sustainable development [256]. The literature on the Energy Union also confirms the importance of the selected dimensions. Andoura and Vinois [125] advocate for flexible regional initiatives with varying degrees of member involvement and responsibility (that is, member tiers), while Turner et al. [144] on its hand indicate the governance instrument itself must be flexible. To Meyer-Ohlendorf [142] the EU energy and climate framework for the 2020 targets is adequate, combining a high-level of obligation with flexible regulation.

In section 6.3 for the first time these dimensions are applied to analyze the European regional governance challenges for an integrated offshore grid. As indicated, the literature identified in the review is used, with a focus on the governance challenges directly related to the integrated offshore grid and the regional level.

6.3. Regional governance challenges

First each challenge identified in the literature review is analyzed through the governance dimensions, and then section 6.4 draws overarching conclusions. Figure 6.3 summarizes the methodology and results. Here, the literature review and the three selected governance dimensions allow to identify the five challenges for the governance of integrated offshore expansions.

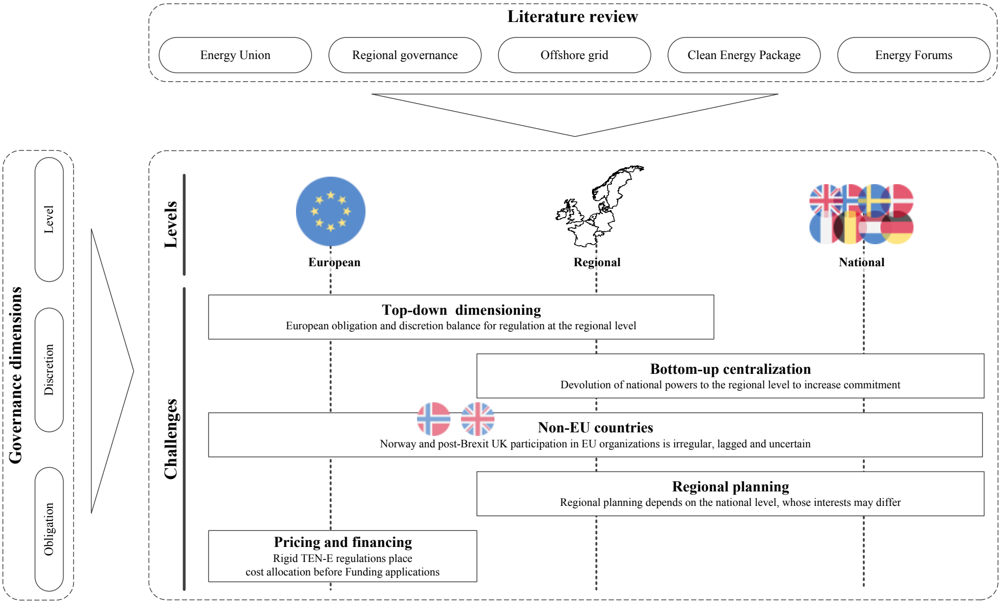

Figure 6.3: Methodology and results summary

The challenges are briefly described in Table 6.1, together with the interaction of different levels and countries. In the following subsections each challenge is detailed. The first three challenges relate to every governance building block indicated by Mekonnen et al. [26], while the last two challenges identified are more specific, relating to certain building blocks.

Table 6.1: Regional governance challenges

Challenges	Description	Main levels	Countries' involvement
Top-down dimensioning	European regulation must balance implementation obligation and discretion at the regional level	European-regional	All North Sea countries
Bottom-up centralization	Regional cooperation depends on voluntary centralization of national powers to achieve adequate obligation and rigidity	Regional-national	
Non-EU countries	Non-EU countries participation in EU organizations for the governance of power system expansion hinders dimension balance	All	
Regional planning	Binding and rigid regulation make regional plans depend on national ones	Regional-national	
Pricing and financing	Funding and cost allocation are interdependent but unsynchronized due to binding and rigid regulation	European	EU countries

6.3.1. Top-down dimensioning challenge: European regulation must balance implementation obligation and discretion at the regional level

As seen in section 2.4, the European centralization of decision-making would allow the consideration of expansions beneficial at the continental level (including integrated ones), avoid the divergence of national regulation, internalize national externalities, and promote regulatory stability. On the other hand, complete centralization of governance is impossible due to actor fragmentation and resistance, and the national sovereignty over the energy mix. And in any case, full centralization is undesirable for a number of reasons. First, cooperation at the regional level is simpler. Second, centralization may hinder experimentation or hold back ambitious frontrunners. For example, ACER [257] recommends to remove integrated projects from the ten-year network development plan (TYNDP), such as the 3rd-party Abengoa Northern Atlantic Interconnection or the two conceptual North Sea projects. Finally, decentralization is more robust to design errors and accounts for heterogeneous national characteristics.

Thus, support for accelerated or obligatory centralization in the governance of power systems is mixed [24,89,243,258]. Recognizing the political difficulty of establishing regional cooperation from the top, Gephart et al. [251] propose 'a mix of top-down and bottom-up elements' combining rigid obligation with flexible implementation, as does the ENTSO-E [259].

Governance at the European level must balance the implementation obligation and discretion to guarantee at the regional levels the advantages of centralization, which in some cases the literature finds adequate. The first case is the novel Clean Energy Package governance regulation, leveraging reputational incentives for cooperation [128]. It requires Member States to develop integrated National

Energy and Climate Plans and periodic reports, following templates with key indicators. It also includes binding but flexible cooperation of Member States and stakeholder consultations on these plans, with the involvement of the Commission. Finally, it also provides for recourse measures by the Commission in the case of insufficient ambition or delivery of European and/or national targets [4,128,138].

With the Clean Energy Package and the Trans-European Networks for Energy (TEN-E) regulation, both renewable energy projects and transmission Projects of Common Interest (PCIs) benefit from simplified permitting, while still providing countries with flexibility on the implementation of the permitting one-stop shops. Also, the Clean Energy Package promotes the convergence of national capacity remuneration mechanisms and support schemes for renewable energy [253,254]. Finally, binding regulation at the European level requires stakeholder consultations conducted by national regulators, TSOs, the ENTSO-E and ACER. Hence, in many aspects European regulation introduces an obligation for implementation while providing flexibility.

On the other hand, in several aspects the literature recommends a different approach to implementation obligation and/or discretion. First, while the 15% interconnection target [4] is binding and rigid, it is too simplistic and contains a number of design flaws [260,261]. This is tempered by a recent expert group report, which points towards a correction of the flaws and a periodic revision of the target methodology [9]. Second, the non-binding nature of cross-border cost allocation agreements for PCIs led to many ‘bridges to nowhere’ in Europe [262].

Third, European organizations such as ACER and ENTSO-E are often mere coordinators, with limited powers and access to data [260,263,264]. For example, the ACER recommendations are generally non-binding, which leads to discrepancies between the national development plans and the TYNDP, shortfalls in ENTSO-E’s cost benefit analysis methodology and differences in national economic incentives for transmission and generation projects [114,265–267]. While the Clean Energy Package adds some powers for ACER regarding network codes and operational aspects [148], expansion responsibilities are largely unchanged for ACER, the ENTSO-E and the Commission.

Fourth, transparency and consultation also need to be improved, both for processes which already include consultation and for more opaque ones such as the work of the TYNDP regional groups [89,261], that which indicates that the implementation is not binding or the discretion too flexible. Fifth, despite the ENTSO-E [24] proposal on Regional Electricity Forums for cooperation in policy and operational aspects, the Energy Union proposal does not comprise any regulation for the formalization of regional initiatives [268]. Finally, the obligatory cooperation between neighboring countries established in the maritime spatial planning directive is difficult, slow and vague [100,112].

These examples support an increased obligation and/or rigidity of European regulation affecting the regional or national level, which may be required where national interests may conflict with regional ones, or where detailed guidelines are necessary to avoid divergence of regulation. However, regulatory obligation or rigidity can also be counterproductive for an integrated offshore grid. This is illustrated by the recommendation of ACER [257] to remove 'non-concrete projects' off the TYNDP, including the conceptual 'Northern Seas offshore grid infrastructure' and 'West-East corridor in the North Sea' projects.

Thus, *reaping the advantages of centralization at the European level for regional cooperation requires a balanced use of binding and rigid regulation, avoiding the disadvantages of centralization through flexible and if necessary non-binding implementation*. Each governance aspect will require the right balance of implementation obligation and discretion, given the potential for regulatory divergence and for conflict of national interests.

While it is acknowledged that the novel Energy Union governance regulation is balanced in these dimensions, there are several examples of obligation or rigidity in transparency and participation, planning, and powers of European organizations. Consequently, rigid regulation which negatively affects integrated offshore projects by discouraging very long-term planning or specific economic incentives should not be binding. For example, the mentioned rigidity in the ACER recommendations on the TYNDP is softened by the fact they are non-binding, still allowing for the inclusion of conceptual integrated projects in the TYNDP.

6.3.2. Bottom-up centralization challenge: Regional cooperation depends on voluntary centralization of national powers

It was indicated that the regional level is pivotal for the governance of the offshore grid expansion [27,111,112]. Generally, there is 'widespread consensus on the fact that regional cooperation should be a key element of the Governance process' [269], on which the ENTSO-E [24] agrees. However, a higher obligation and rigidity at the regional level can be necessary to escape the disadvantages of regional cooperation. For example, Müller [112] considers the TYNDP inadequate as an offshore infrastructure plan because its implementation is not binding. Hence, commitment based on a shared vision is emphasized by many actors and researchers, and higher obligation and rigidity can contribute to creating and enforcing commitment [27,62,63,111,115].

Nonetheless, there is no agreement on the level of enforcement needed to guarantee actor commitment to an integrated grid or the Energy Union, and on the formalization of the enforcement instruments. The need for formalization of regional cooperation is also not consensual [259,269,270]. For example, the Renewables Grid Initiative questions the transfer of some operational responsibilities under the Clean Energy Package from TSOs to regional organizations [270].

According to Steinbacher and Schoenefeld [145] polycentric governance scholars advocate 'flexible entry and exit from regions', while the ENTSO-E [24,107] supports the top-down definition of regional initiatives combined with flexible definition of their scope of cooperation. To Meyer-Ohlendorf [142], a 2030 EU energy and climate policy 'governance system that is largely based on political commitments with no legal basis risks undoing much of the success accomplished by the current system', while Andoura and Vinois [125] support binding rules 'properly implemented by the actors in a collective way'. Finally, Danson [248] doubts a North Sea regional initiative will be formalized in the short-term, but questions whether this is necessary at all for cooperation.

Currently, there are multiple active groups fostering the cooperation of North Sea countries. These comprise the North Sea group of the TYNDP, the Northern Seas offshore grid group of the TEN-E, the North Seas Countries' Offshore Grid Initiative (NSCOGI), the North Sea Region Programme, and more recently the North Seas Energy Cooperation initiative sponsored by the Commission (with its associated North Seas Energy Forum). However, participation and any resulting integrated expansion plans are not binding even in initiatives directly related to the integrated offshore grid. Thus, to Müller [112] regional initiatives such as the North Seas Countries' Offshore Grid Initiative are useful but do not have adequate penalties to ensure commitment.

The *implementation obligation and rigidity can partially be established by top-down regulation* at the European level. However, this is limited for a number of reasons, as discussed in the top-down dimensioning challenge. Given the gap in and importance of regional commitment that the literature indicates, *obligation and rigidity at the regional level must be partly achieved by voluntary centralization of powers* by North Sea countries, as proposed by Müller [112]. This will be more pressing once initiatives such as the North Seas Energy Cooperation delivers actionable, integrated expansion plans. *The present challenge thus requires countries to relinquish powers for the regional benefit, possibly to their disadvantage* (which is further discussed in section 6.3.5). Although the Commission plays an important role sponsoring the North Seas Energy Cooperation initiative, this is not formalized in any way in the Clean Energy Package. Moreover, regional initiatives are also not addressed in the integrated National Energy and Climate Plans as a mean to incentivize regional cooperation and the centralization of national powers – the plans just indicate specific cooperation measures, for example on renewable energy or interconnection.

6.3.3. Non-EU countries challenge: Between full and no participation in EU organizations for the governance of the power system expansion

The ENTSO-E [107] highlights the necessity to involve strongly-interconnected non-EU countries in regional initiatives for operation. It also calls for the participation of European Economic Area (EEA), European Free Trade Association and Energy Community members in its proposed Regional Electricity Forums [24].

For the North Sea, Norway and the UK are indeed pivotal for regional cooperation [92,248]. Specifically for the integrated offshore grid, many important pilot projects require either or both countries, such as the UK-Benelux or UK-Norway clusters [28]. Also, chapter 5 demonstrated that national vetoes to an integrated grid have a negative impact to European welfare. Finally, beyond the specific participation of these countries in the offshore grid governance, this could provide a more general solution to the involvement of non-EU countries in the European energy sector [271] and in other future offshore grids such as in the Mediterranean. Thus, there is both the necessity and interest in involving Norway and the UK in the offshore grid governance.

Norway is a full member of the ENTSO-E, the Council of European Energy Regulators and the North Seas Energy Cooperation, as well as an observer in ACER [25,92]. Moreover, the adoption of the Third Energy Package in 2017 by the European Free Trade Agreement will allow Norway to become a full member of ACER [92,272]. However, as a non-EU country it is not part of the TEN-E groups [17].

As for the UK, it is currently a full member of all of the abovementioned organizations, but with Brexit its place is still uncertain. None of the existing solutions for non-EU countries are applicable to the UK, namely membership of the European Economic Area or Energy Community, or tailored agreements as for Switzerland [271,273,274]. Full participation in European organizations such as ACER, ENTSO-E and regional initiatives are possible, as long as energy and environmental legislation are continuously adopted into British law, and to Froggatt et al. [271] the UK is likely to incorporate the Clean Energy Package before Brexit. Moreover, actors generally indicate it is in the interest of the UK and Norway to exert as much influence as possible in European energy decision-making [92,271]. Also, many relevant regional initiatives and organizations such as the North Seas Energy Cooperation and Forum require no formal obligation on being a Member State, which provides flexibility for the participation of the UK or Norway. Nonetheless the uncertainty engendered by Brexit impacts the participation of the UK in the integrated offshore grid governance.

The participation spectrum on formal EU organizations and institutions goes from full (exclusive to Member States) to no participation (with the country being always a 3rd-party and establishing specific bilateral agreements). While Norway is closer to full participation, the lag in the adoption of EU regulation and its status as a European Economic Area member impose limits to this. On the other hand, the EU and the UK will need to find a solution which will likely be closer to the other end of the spectrum, though the UK will want to remain in the internal electricity market [271].

Full participation in European and regional organizations entails a higher obligation and rigidity, which provides some of the advantages of centralization at these levels. However, this comes at the cost of flexibility – thus the exit of the UK from these organizations may provide greater flexibility for the deployment of the integrated offshore grid. However, the complete exit of the UK from European organizations is unlikely. Thus, *there is a challenge regarding Norway and the UK:*

their involvement lies somewhere in the middle of the participation spectrum, restricting the advantages of either higher or lower implementation obligation and/or discretion. While solutions theoretically exist for this challenge, the EU regulation adoption lag (for Norway) and the lack of clear solutions (for the UK) leave it a relevant and pressing issue, given the importance of these countries to integrated offshore projects. However, *the Energy Union does not change the current framework for the involvement of non-EU countries in energy and climate organizations and institutions.*

6.3.4. Regional planning challenge: Binding and rigid regulation make regional plans depend on national ones

So far, only challenges which can theoretically be addressed were indicated. Now two challenges arising from contradictory regulation at the European level are discussed, which are not solved by the Clean Energy Package. The first one is related to the regional planning of integrated projects. This challenge is connected to the bottom-up centralization challenge, but is moreover particular to the governance building block of planning and relates to specific contradictory regulatory issues as indicated.

As chapter 4 and 5 indicate, for integrated projects to compete with non-integrated transmission and generation projects on an equal footing, they need to be explicitly considered at the regional level in the planning phase. Many actors advocate the deployment of integrated pilot projects as a first step towards an integrated grid, promoting cooperation, innovating, and reducing uncertainty [25,28]. However, it was indicated that there are currently only a handful of integrated projects in different development stages. Moreover, the lead time for the development of pilot projects is long - in an optimistic time frame new ones would be commissioned only after 2025 [275]. Given the scarcity and lead time of integrated projects, it is thus necessary to identify and plan them as soon as possible in order to start the deployment of an integrated offshore grid and reduce uncertainty.

The North Sea regional group of the TYNDP did include some offshore integrated projects in the North Sea, Atlantic and Irish channel in its last investment plan [276]. In addition, the integrated projects of the Kriegers Flak Combined Grid Solution and the COBRA interconnector (which considers the connection of offshore wind farms) are currently being implemented with support of the TEN-E regulation [252,277]. Also, the North Seas Energy Cooperation initiative plans to develop an integrated offshore plan and concrete proposals for pilot projects by 2019 [278,279].

Nonetheless, these concrete examples are few, which is partly due to the regional planning challenge, as follows. Currently, projects in the TYNDP regional investment plans originate exclusively from the national development plans or from the proposal of independent developers. However, national regulators and thus TSOs are required to consider the national interest for expansion planning. This leads Gaventa [261] to recommend that national regulators need to be authorized to consider regional interests and priorities. For example, the Britib (Britain-Iberia) offshore interconnector linking Spain to the UK through France was 'rejected by the ministry' [257], and thus not included in the Spanish national development plan. Also, independent developers are less likely to develop integrated projects than regulated TSOs. For example, Meeus [54] indicates that the 'TSO model' is the most suitable in order to develop an integrated offshore grid, as opposed to a 'generator model'. Moreover, for a project to qualify as a PCI, it needs to be included in the TYNDP[a]. Hence, TYNDP and TEN-E groups play a passive role, not being able to set regional objectives, or solicit or propose new projects [261].

Hence, *regional planning for integrated projects is dependent on plans developed at the national level, where the national interest may conflict with the regional one.* This constitutes the regional planning challenge, where integrated projects face a barrier due to a contradiction arising from current regulation. Moreover, due to various regulatory and methodological differences this set-up also leads to an increasing inconsistency between the TYNDP and national development plans, as identified by ACER [257,280]. This 'raises doubts on the credibility and feasibility of the implementation of many TYNDP projects' [260].

Many indicate that the future governance framework should change to consider the regional and European interest. Hence, to ACER [281] the regulatory framework of the future will 'support economic investment in networks, without discriminating between national and cross-border projects, to the benefit of consumers'. De Clercq et al. [106] proposes that in the long-run all project assessments (regulated or not) should be conducted by an independent regulator. A shift to improved regional planning is advocated also by Delhaute et al. [27], Müller [112] and Gaventa [261].

Therefore, *the European regulation as revised by the Clean Energy Package maintains a binding process whose rigidity makes regional plans dependent of the national level and does not provide the flexibility for the consideration of integrated projects.* Providing a level-playing planning field for integrated projects requires addressing this challenge, which is pressing given their scarcity and development lead time.

6.3.5. Pricing and financing challenge - European PCI funding and cost allocation are interdependent but unsynchronized

The pricing and financing challenge follows naturally from the regional planning challenge of section 6.3.4. There it is indicated that the planning of integrated projects must consider the regional interest. However, there can be a strong asymmetry of welfare distribution among countries and actors, with integrated

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[a] Annex III.2(3) of the TEN-E regulation [17]

projects possibly reducing the welfare of some North Sea countries. Hence, the distribution of costs and benefits among hosting and neighboring countries is one of the main barriers to an offshore grid, as seen in chapter 5 [27,29]. In the cases where a hosting country is harmed by an integrated offshore project, cross-border cost allocation is necessary to align the country's interests to the regional one. Also, adequate public financing is an important issue for integrated offshore and transmission projects in general [116]. TEN-E guidelines allow for cross-border cost allocation in PCIs and provide financing from the Connecting Europe Facility [17], and the Clean Energy Package maintains this cost allocation and financing measures for Projects of Common Interest basically unaltered.

ACER recommendations and ENTSO-E guidelines set up the implementation discretion for cost allocation [265,282]. Hosting TSOs are responsible for reaching an agreement, with ACER acting as a recourse decision-maker. ACER recommends that countries positively affected by the project above a significance threshold of 10% of positive net benefits contribute through cost allocation, but this is non-binding. Usually, PCI investment costs are equally split among hosting countries, with exceptions such as the Estonia-Latvia interconnection, which did have a non-standard (10/90%) allocation of costs [283]. Non-standard cost allocation agreements are a relevant instrument to enable integrated offshore projects in the future, but there are only a few cross-border electricity PCIs with non-standard cost allocation.

In addition, many electricity PCIs make extensive use of the Connecting Europe Facility grants to cover a financing gap of up to 75% [283]. Cost allocation agreements are a requirement for, and thus take place before any Facility funding applications [17]. Hence, all projects depending on Facility funding assume ex-ante that the application will be successful. However, this may not be the case, generating a finance gap, which would compromise the agreed-upon cost allocation and consequently the project. This asynchronicity between the cost allocation and the Connecting Europe Facility is named here the *pricing and financing challenge*, and is mentioned by multiple stakeholders [284–286]. Erdem [285] supports changes to the TEN-E regulation to conduct the cost allocation and funding applications in parallel and with the cooperation of European and national organizations responsible for the decision. Another solution would be to develop ex-ante adjustments conditional on the funding application outcome, but this is not consensual. For example, ACER [287] is against cost allocation being 'conditional on potential future public funding', although it tolerates 'ex-ante defined adjustments' for cost deviations.

Despite the lack of consensus on the solution, the challenge does exist: while applying for Connecting Europe Facility funds is not mandatory for PCIs and thus not binding, the TEN-E regulation is rigid in this financing aspect, placing cost allocation agreements before Facility applications. This despite them being interdependent, with several electricity PCIs depending on Facility funding. The TEN-E regulation does allow for ex-ante agreements on the reallocation of costs pending on the ex-post realization of the PCI benefits, but although encouraged by ACER this is little used and does not solve the uncertainty arising from the possible rejection of the application to Facility funds. An aspect which further complicates reaching adequate cost allocation agreements for the offshore grid are the current shortcomings of cost-benefit analysis methodologies [114]. Although it is not discussed further here, for this relates not only to offshore but also to onshore transmission projects, the current shortcomings impede the acceptance of cost-benefit analyses by all parties. This lack of trust in the cost-benefit analyses consequently compromises reaching adequate and acceptable cost allocation agreements, as indicated in the evaluation of the TEN-E regulation [288].

6.4. Conclusions

Regional governance is attracting attention as the adequate decision-making mode to conduct expansions for the European and other multi-level, multi-actor power systems. *This chapter highlights the implementation obligation and discretion of regulation at different levels for a number of challenges.* The offshore grid is a 'blank slate' where these challenges are prominent because of the importance of regional expansion and the potential for integrated projects. This contrast to onshore grids, which are more developed, limiting the possibilities for integrated projects. This addresses the last subordinate research question, on the adequacy of the current European expansion governance framework to enable the integrated offshore grid.

The first two challenges identified deal with the interaction in the governance structure of the European and national levels with the regional one. In this way, they are centered on the vertical interaction of governance (between the levels). In contrast, the non-EU countries challenge deals with the participation of these countries in the European governance of expansion. Thus, it concerns mainly the horizontal interaction of countries in European, regional and national organizations.

The last two challenges identified are more specific than the first three. Beyond involving the interaction of particular levels, they concern specific governance building blocks – planning, and financing & pricing, respectively. These challenges indicate contradictions arising from particular regulations of the European governance of offshore expansion.

Subsequently, after identifying these challenges it was asked how the regulatory reform of the Clean Energy Package affects them. It was indicated that the governance proposal does bring positive but limited changes to the top-down dimensioning challenge. However, the Clean Energy Package measures affecting the European power sector focus the energy and climate targets governance, and the power system operation. Thus, the regional governance of expansions remains largely unchanged, and most of the challenges identified are unaddressed.

The analysis only identifies the challenges, but now some considerations in how to tackle them are made. For this, one must consider how fast European regulation can be modified. The offshore grid governance expansion framework and projects exhibit significant inertia. As seen, new integrated projects will take a decade or more to develop, and the Energy Union governance revision will take place only in 2026. Also, the Commission conducted an evaluation of the TEN-E regulation in 2017, but prioritized non-legislative changes [288].

Hence, non-binding and flexible governance regulation and measures are all the more important because implementing and modifying them is faster. An example of a flexible, non-binding measure would be the development by ACER of guidelines on the inclusion of concept integrated projects in the Ten-Year Network Development Plan (and consequently as Projects of Common Interest). On the other hand, the bottom-up centralization challenge highlights the limitations of top-down regulations and measures, by stressing the importance of achieving sufficient obligation through the voluntary centralization of powers to the regional level.

By July 2018 the European Commission, Parliament and Council trilogue reached an agreement on parts of the Clean Energy Package, such as the governance and renewable energy regulations. The amendments proposed by the Council or Parliament contain some advances in specific points of the original Commission proposal. For example, on the planning and reporting of investment strategies and of infrastructure projects other than for transmission and distribution (i.e., including generation and storage). It also includes further details on the European financing mechanism for renewable energy projects, and on involving previously-existing regional cooperation organizations such as the North Seas Countries' Offshore Grid Initiative. Additionally, the Parliament proposals establish a multilevel climate and energy dialogue platform and the possibility of involvement of European Economic Area members in the Energy Union governance. These could enhance the regional cooperation and the participation of stakeholders such as civil and business organizations. However, the final regulations are not published yet, and they are anyhow insufficient to adequately address the challenges.

Finally, the analysis using the dimensions opens up relevant areas of research for the offshore grid and regional governance of expansions. To begin with, the first three challenges (which are more general) can be further detailed for each of the governance building blocks of Mekonnen et al. [26] concerning specific regulations and their obligation and discretion. Second, the regional interconnection of onshore systems (in Europe and the US) and the discussion on other offshore grids (in Europe, the United States and Asia) is gaining momentum [19,73,104]. The methodology can therefore be broadened and replicated to other regional grids, further advancing regional expansion planning theory. Third, the consideration of governance at the regional level can be assessed versus alternatives such as pan-European and project-specific approaches considering various criteria, for example political acceptability and implementation feasibility. Finally, the single-sector focus can be broadened to research cross-sectoral integration in marine governance [100], following the research agenda proposed by van Tatenhove et al. [245].

7 Looking back and forward

The main research question of this thesis aimed to understand how the expansion pathway of the North Seas offshore grid can be governed towards more integration. In order to address this and the subordinate research questions presented in section 1.2, the thesis leveraged diverse methodologies as presented in Figure 1.1. Complementary qualitative and quantitative methodologies provide both normative and exploratory expansion pathways and analyze the current expansion governance adequacy. This last chapter summarizes the answers to the research questions on the expansion governance of the integrated North Seas offshore grid. It also reflects on the results and makes policy recommendations organized following the governance building blocks of meta-governance, planning, and financing & pricing.

7.1. Conclusions

The main research question addresses three aspects: which actors affect the expansion pathways, which shape decision-making should take to enable the integrated grid, and at which level. As indicated in chapter 1, this acknowledges that the grid expansion pathway will combine conventional and integrated assets and that it cannot be governed by any single European actor. The four subordinate research questions are now presented sequentially in order to provide an answer to the main research question. Each research question makes a number of policy and scientific contributions as summarized in Figure 7.1.

7.1.1. Research question 1

How do actors in the European power system affect the offshore expansion pathway?

Chapter 2 addresses how offshore expansion pathways can be governed. It indicates that due to the characteristics of the North Seas offshore grid, *investments in offshore power transmission and generation are central to determine the expansion pathway*. Especially, generation and transmission assets are large, capital intensive, durable and specific, and expansion pathways are characterized by path dependence. Thus, management of investments is more important to the offshore grid expansion than that of operations. Nonetheless, operational management still affects investments decisions, albeit limitedly.

Moreover, due to the uncertainty of this expansion pathway and the multi-level and multi-actor characteristics of the grid, the capacity of any single actor to steer this pathway is limited. This makes purely hierarchical modes of decision-making inadequate to govern the pathway. Thus, *governance is the most adequate decision-making mode for the expansion of the offshore grid*. Governance combines the coordination forms of hierarchies, markets and networks to make decisions in a networked multi-level, multi-actor system.

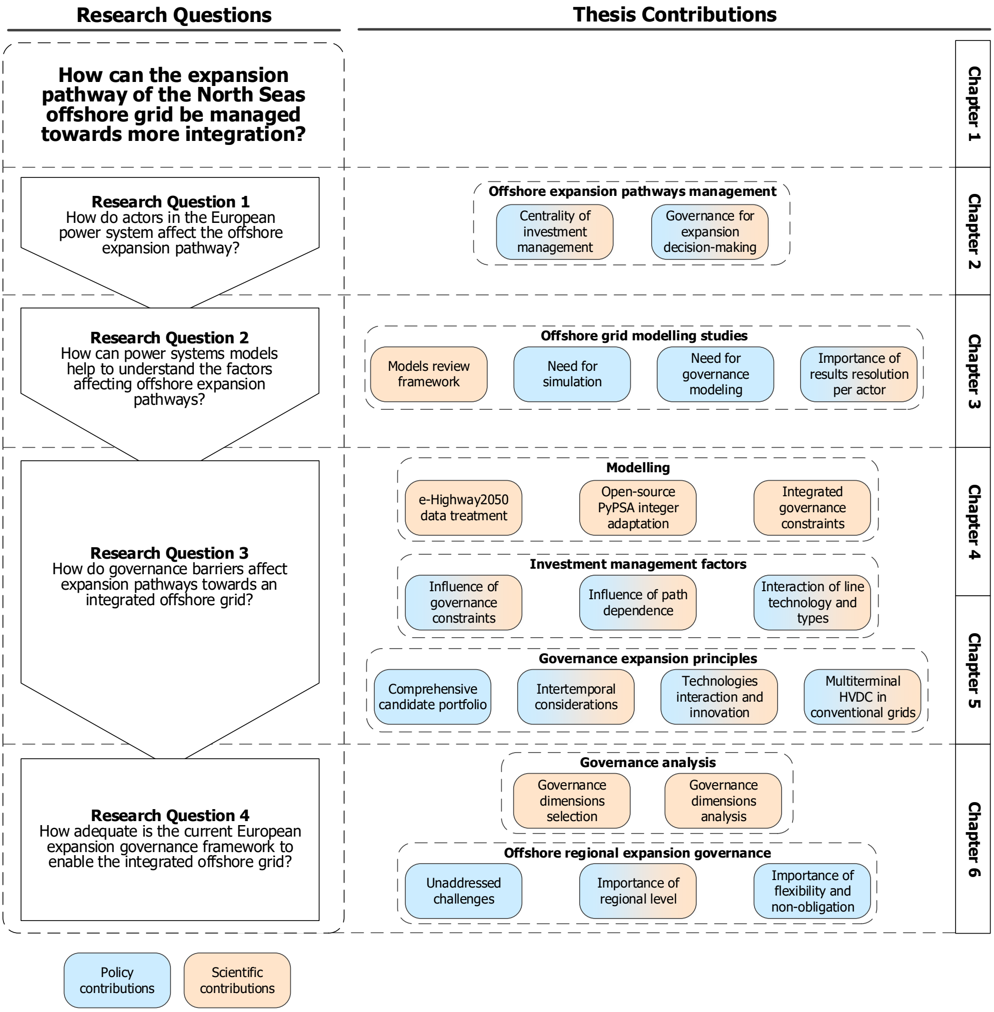

Figure 7.1: Scientific and policy contributions

Chapter 2 presents six building blocks which address several aspects of the expansion governance of the North Seas offshore grid. The literature indicates that barriers in the planning and pricing building blocks are particularly relevant to developing an integrated offshore grid, comprising specifically the costs and benefits allocation, the support schemes for offshore wind and the integrated site planning and development.

In summary, actors affect the offshore expansion pathway with the management of investments conducted through governance, interacting in all six governance building blocks. This then opens the issue of how different methodologies can support the investment management of the offshore grid through governance, by studying the specific barriers. Thus, chapters 3 to 5 analyzed and leveraged quantitative energy systems modeling, while chapter 6 leveraged regulatory analysis as a qualitative methodology.

7.1.2. Research question 2

Which factors affect offshore expansion pathways as informed by offshore grid models?

Chapter 3 analyzes models on the North Seas offshore grid through a *review framework comprising the system characteristics, review categories and indicators*. This triple approach constitutes a comprehensive review methodology, contributing to future energy systems modeling reviews. With these multiple analysis perspectives, the review identifies a series of improvement areas for models of the offshore grid, of which three are particularly relevant.

The first important result of the model review is the identification of a *gap in the utilization of bottom-up simulation models to study the offshore grid*. Indeed, the large majority of models reviewed use bottom-up optimization. Optimization provides a meaningful normative approach to study the offshore grid. These optimization studies indicate that the expansion of the offshore grid is beneficial to Europe, especially if it involves integrated assets. Nonetheless, the range of these identified benefits among studies is still broad. More importantly, given the predominance of optimization studies, simulation models can complementarily explore expansion pathways with a more detailed representation of the system.

Second, chapter 2 indicates that governance is central to the expansion of the offshore grid. However, the review identifies a *gap in the endogenous representation of expansion governance in offshore grid models*, although this is moderated by more recent studies. The importance of this gap increases due to the influence on integrated lines of the distribution of costs and benefits and to the planning complexity.

Third, *the reviewed studies frequently model and present the distribution of costs and benefits at an insufficient resolution*, despite their importance as a barrier to an integrated offshore grid. That is, the distribution is more often considered at the European or national than the actor level. This precludes any analysis of the consequences of this distribution among countries and actors on the development of integrated lines. It also bars the study of cost allocation mechanisms, which could address barriers arising from costs and benefits distribution issues.

Thus, on the one hand the review conducted in chapter 3 indicates how optimization models helped to understand normative expansion pathways for the offshore grid and their benefits. On the other hand, it identifies three interrelated research gaps which advocate for offshore expansion simulation models endogenously representing governance. These would naturally require a higher resolution in the distribution of costs and benefits than most models reviewed.

7.1.3. Research question 3

How do governance barriers affect expansion pathways towards an integrated offshore grid?

The Exploratory Offshore Grid Model (OGEM) presented in chapters 4 and 5 addresses the modeling gaps identified in chapter 3. The central contributions of OGEM are modeling the expansion of the offshore grid through simulation, studying the investment management factors with integrated governance constraints, and finally developing governance expansion principles.

First, in order to address the identified gaps of chapter 3, OGEM provides an *open-source adaptation of the Python for Power Systems Analysis (PyPSA) toolbox, including integrated governance constraints*. These constraints address the distribution of costs and benefits (the welfare constraints) and the planning complexity (the integration constraints). The former include the Pareto and Kaldor-Hicks constraints, while the latter comprise the complex integration and disintegrated constraints. These constraints are more complex than in previous offshore grid models, which at most represented the planning complexity by excluding integrated lines altogether from the portfolio of expansion candidates. This contributes to the modeling of any power system where planning and pricing barriers arise from the multiplicity of networked actors and decision-making levels.

Second, with the integrated governance constraints OGEM draws *three main observations from the exploration of offshore expansion pathways: on the influence of these constraints on European welfare gains, on the interaction of constraints with transmission lines technologies and types (conventional or integrated), and on the importance of path dependence.* First, the integrated governance constraints impact negatively the welfare gains to Europe, countries and actors. However, this negative impact is modest in absolute terms. Nonetheless, the potential of losing countries to limit their own losses through the veto of integrated lines is limited. Second, investment management factors interact significantly with governance constraints, especially the path dependence and line technologies and types. Hence, the impact of governance constraints on the deployment of line technologies and types is stronger than on the European welfare gains. Also, national vetoes to integrated lines significantly alter the typology of the offshore grid. Third, the expansion path dependence is strong, exhibiting a particular influence on the deployment of multiterminal HVDC lines, which exhibit larger synergy. Nonetheless, this path dependence is not absolute, so integrated or multiterminal HVDC lines may still be deployed in different pathways if they are very beneficial.

As the third contribution of OGEM, the exploration of the offshore expansion pathways provides for four governance expansion principles for the North Seas offshore grid. The first concerns the *need to consider a comprehensive candidate portfolio which includes integrated assets*, in order to provide a level-playing field to the integrated offshore grid. Second, given the strength of path dependence, *intertemporal considerations are central to the expansion governance*. That is, expansion governance needs to consider the interaction of sequential offshore expansion periods. Third, *expansion governance needs to consider the interaction of transmission technologies* (HVAC, point-to-point HVDC and multiterminal HVDC) in their candidate portfolio and modeling. This includes considering transmission innovations which may alter the relative attractiveness of each transmission technology (such as DC breakers). Finally, although multiterminal HVDC and integrated lines exhibit a high interaction, they are not totally interdependent. Thus, *there is the possibility of deploying multiterminal HVDC lines even in a conventional, non-integrated offshore grid.* Although this is a second-best solution when compared to an integrated offshore grid, expansion governance needs to adequately consider conventional multiterminal HVDC lines.

7.1.4. Research question 4

> How adequate is the current European expansion governance framework to enable the integrated offshore grid?

Chapter 6 develops an analysis of the expansion governance framework for an integrated offshore grid in the North Sea region considering the changes brought by the Energy Union. This qualitative analysis complements the quantitative modeling of chapters 4 to 5. The methodology developed can also be applied to the analysis of expansion governance frameworks in other power systems, while the results provide a number of insights on the European regional offshore governance.

The governance analysis framework first selects a number of governance dimensions. In chapter 6, the selected dimensions are the implementation obligation, discretion, and level. Obligation indicates whether the European expansion regulation is binding or non-binding. Then, discretion refers to whether the implementation is rigid or flexible. Finally, the last dimension analyzes the interaction of the European, regional and national levels. These dimensions derive their relevance from two considerations. The first is the importance of the North Seas regional level to the offshore grid. The second is the conflict between providing sufficient flexibility to regional and national expansion planning while guaranteeing commitment to integrated projects, in a context of limited powers of European and regional actors.

The application of this governance analysis framework leads to *five challenges for the regional governance of the offshore grid expansion*. The first three challenges address the interaction of expansion governance at the European and national levels with the regional one, and the involvement of countries outside of the European Union (the United Kingdom and Norway).

On the other hand, *the last two challenges relate to conflicts in current European regulations regarding specific governance building blocks.* Thus, the fourth challenge identifies a dependence of regional expansion planning on the national development plans. Then, the fifth and last challenge identifies a conflict between financing and cost distribution mechanisms for European Projects of Common Interest, which arguably includes most current and future integrated offshore projects.

The challenges highlight two aspects for the expansion governance of the offshore grid. The first one is *the importance of the regional level for expansion governance.* This is an aspect which is rising in prominence not only in Europe but also in other regions. Second, given the inertia in the European regulatory process and in the development of integrated offshore projects, it becomes *paramount to achieve flexible and non-obligatory regulation for the European expansion governance.* This aspect should guide future regulatory reforms addressing the identified challenges.

In summary, by identifying the challenges for the regional expansion governance of the offshore grid, chapter 6 assesses the adequacy of the current European energy and climate regulation. The analysis conclusions indicate that *the regulatory changes of the Clean Energy for All Europeans Package leave the challenges mostly unaddressed.*

7.2. Policy recommendations

The combined chapters address the main research question:

> How can the expansion pathway of the North Seas offshore grid be governed towards more integration?

Developing an integrated grid requires managing investments in offshore transmission and generation assets. Moreover, given a multi-level and multi-actor system with uncertainty on the offshore expansion pathway, governance is the only adequate and possible decision-making mode. This research results in policy recommendations in four governance building blocks: meta-governance, planning, and financing & pricing.

The meta-governance recommendation concerns capacity building at the regional level, with the corresponding commitment of resources. The analysis of the Clean Energy Package highlighted the importance of the regional level for expansion governance. North Seas countries need to build an organization at the regional level capable of addressing the complex and multi-faceted aspects in all governance building blocks. The North Seas Energy Cooperation is a welcome step forward, but further resources and commitment is needed, possibly in the form of the Regional Electricity Forums proposed by the ENTSO-E.

There are multiple recommendations regarding planning. First, the planning challenge needs to be addressed: currently, regional planning does not provide regional groups with the flexibility to consider integrated projects. At present, the regional project portfolio is fed from National Development Plans and third-party projects. Regional groups of the Ten-Year Network Development Plan and the

Trans-European Networks for Energy need to be allowed to include and evaluate integrated offshore projects.

This would contribute to the second planning recommendation: regional initiatives need to build a larger portfolio of integrated projects. Currently, the number of integrated pilot projects is small and the lead time to develop projects can be longer than a decade. The offshore grids work group of the North Seas Energy Cooperation aims to deliver 'agreement[s] between developers, industry and authorities on steps towards the development of concrete [integrated] projects' [279]. Deploying more integrated projects by 2030 requires immediate action, and the leadership of this organization is crucial to building-up a larger project portfolio.

Then, the third planning recommendation concerns the consideration of conventional multiterminal HVDC lines in the project portfolio. As indicated, even when integrated lines are not possible, multiterminal lines can still be beneficial at the regional and European levels. Moreover, they can later be leveraged to deploy integrated multiterminal lines. Thus, regional expansion plans for the North Seas should also consider conventional multiterminal HVDC interconnectors and farm connectors. This expansion could interact with a multiterminal HVDC overlay grid onshore.

Fourth, once the candidate portfolio includes both integrated and conventional offshore projects, planners need to consider that innovation will affect transmission technologies differently. Thus, regional planning should for example conduct a sensitivity analysis on the costs and benefits of each project with varying cost assumptions for each transmission technology, which is not presently the case.

Conducting sensitivity analyses would increase the complexity of the regional planning process. Thus, the last planning recommendation concerns open-source expansion planning models with public and detailed input and output data and documentation. These would first bring many benefits as often advanced by the open-modeling community. In addition, it would streamline the expansion planning process and facilitate the proposed sensitivity analysis. Moreover, it would also foster a common understanding among the multiple actors in offshore governance. Finally, it would improve the comparability of integrated and conventional projects and of transmission technologies.

Lastly, there are two recommendations concerning the pricing and financing governance building blocks. First, as this thesis indicates, the offshore expansion pathways are marked by strong path dependence. Thus, regulatory mechanisms for project remuneration need to enable anticipatory investments permitting the development of projects into integrated configurations (including the consideration of e.g. vendor interoperability). These are already allowed in many North Seas countries. However, methodologies need to provide the clarity and certainty necessary for transmission system operators to realize reasonable anticipatory investments enabling integrated offshore projects, while avoiding the risk of overinvestments.

The second and final recommendation concerns the pricing and financing challenge of the Trans-European Networks for Energy (TEN-E) regulation. The regulation must avoid cross-border cost allocation agreements becoming invalid due to unsuccessful Connecting Europe Facility funding applications. This could be done through conditional cost allocation agreements which considered both successful and unsuccessful applications for funding.

7.3. Reflections

The normative and exploratory insights into offshore expansion pathways can greatly help the design of a governance framework which enables integrated projects. However, even when combining different modeling or qualitative approaches, there are limits to our ability to fully understand and control offshore expansion pathways.

A first important consideration of OGEM concerns the modelling of offshore platform costs and their separation from converter costs. As offshore platform costs are significant their inclusion would significantly alter the simulation expansion pathways. This possibly to the advantage of integrated projects employing multiterminal HVDC, which could require less platforms (or of a lower capacity).

These limits also include our ability to define the net benefits of such an integrated grid, on which there is great uncertainty. Auctions are becoming the mainstream mechanism for offshore wind development in most North Seas countries. Auctions reveal the actual (falling) cost of these projects, instead of relying on cost models. This thesis indicated there are still significant uncertainties concerning the costs and benefits (monetary or otherwise) of integrated offshore projects. Therefore, auctions can be used to both develop these projects and reveal their true cost. Reducing this uncertainty would boost further integrated projects in the North Seas. Of course, conducting an auction is dependent on the availability of integrated projects. Thus, this is related to the recommendation of enlarging the integrated project portfolio.

As seen, the integrated offshore grid brings also non-monetary benefits concerning European integration, industrial competitiveness and innovation, and the environment. These benefits have the potential to largely surpass any monetary benefits resulting from an integrated grid. Thus, while the integrated offshore grid needs to benefit Europe in monetary terms, this is not enough. Governments and actors need to perceive the intangible benefits of such a grid, which means that the decision for offshore integration is ultimately a political one. Perceiving the intangible benefits could also motivate actors into fostering citizen co-ownership of offshore wind. This would increase public participation in the last European bulwark of centralized, large-scale power generation.

In the last years some developments provide hope for the development of an integrated grid. Some integrated projects began to be implemented, while the North Seas Energy Cooperation revived regional cooperation. However, given the barriers to the integrated development of the grid, even strong political support may be insufficient. Thus, the expansion pathway of the grid may just prove to be a non-integrated one. However, this will not prove wrong the studies which advocated an integrated grid due to its economic benefits. The benefits exist, but the grid may still not materialize due to multiple other barriers.

Without an integrated offshore grid, Europe would lose a project bringing various monetary and intangible benefits. The offshore grid can serve as a seed for further, much-needed regional cooperation. This in the same way that previous regional initiatives resulted in broader cooperation in many areas, being even at the origin of the European Union itself.

Developing an integrated offshore grid also needs to consider the broader picture of the North Seas. This thesis explored the cooperation among countries, but one must take into account the various marine sectors present. Governance of expansions thus happens in the overarching context of marine governance in general [245]. There are conflicts between the various marine actors and with environmental protection values, but also potential synergies.

The governance of the North Seas offshore grid clearly involves multiple aspects. The same way as there is uncertainty on the actual future offshore expansion pathway, the policy recommendations of this thesis are only a starting point to addressing the issues identified. Developing an adequate governance framework and the integrated offshore grid is a continuous, ever-changing task for Europe.

7.4. Future research

By leveraging complementary methods this thesis arrives at exploratory and prescriptive conclusions for the offshore grid. On one side, it explores the influence of investment management factors and governance constraints in expansion pathways of the offshore grid. On the other side, it identifies regional governance regulatory challenges which should be addressed to enable an integrated offshore grid. Nonetheless, there are several research avenues left to understand the expansion governance of the integrate North Seas offshore grid. This section covers the main avenues left for exploration.

First, transmission is only one of the flexibility resources available to address the challenges of the European power system. Thus, technologies such as storage and demand-side management can interact with transmission both in the investment and operational horizons, either complementing or substituting offshore transmission. Moreover, the case studies use investment costs for bottom-founded offshore wind turbines, while from 2030 on floating turbines could play a significant part in offshore wind development in deeper waters, albeit still at a higher cost. There is therefore the need to understand the influence of future energy technologies on the expansion of the offshore grid by leveraging a simulation model representing governance barriers.

Second, cost allocation mechanisms are particularly important to the offshore grid given the centrality of the distribution of costs and benefits to the expansion of the grid. Chapters 4 and 5 indicate that the welfare constraints have a strong influence on the line technologies and types of the grid. Cost allocation mechanisms could enable integrated multiterminal HVDC lines, increasing European welfare gains. Cost allocation requires the availability of information on welfare gains and losses per country, which is the case for both versions of OGEM presented in chapters 4 and 5. Thus, OGEM can be extended in order to consider different cost allocation mechanisms, identifying its impact on the offshore grid expansion and the advantages and disadvantages of each mechanism. There are already studies proposing principles and evaluating different cost allocation mechanisms, but no research exists which combines these with a simulation model representing governance barriers.

Third, chapter 6 conducts a regulatory analysis of the regional expansion governance in Europe, identifying challenges which need to be addressed. However, the analysis does not present concrete legislative proposals to address these challenges. There is therefore the need to evaluate the advantages, disadvantages and feasibility of alternative changes to the current governance framework. Any such analysis needs to consider the regulatory and project development inertia indicated in chapter 6 and its influence on the compromises in the regulation implementation level, obligation and discretion.

Fourth, the existing versions of OGEM do not consider the security of supply. That is, the expansion model does not consider the behavior of the system under non-forecasted disturbances. However, this security of supply is one of the criteria applied in the European cost-benefit analysis of transmission expansion plans. The consideration of security of supply should influence the interaction of the governance constraints with other investment management factors.

OGEM also does not model the standardization and vendor interoperability of different integrated projects employing multiterminal HVDC. As recent research indicates this as an important aspect, a more detailed modelling of such aspects could provide insights on its interaction with the governance constraints.

Finally, the main research avenue left concerns the regional development of the North Seas mentioned in the reflections. This must consider not only the offshore grid but also other offshore uses (economic, military, recreational) and the environment. Qualitative and quantitative research on the offshore grid could study the influence of this integrated marine governance on the expansion pathways. Bottom-up energy systems modeling is already moving towards the co-modeling of multiple economic sectors, while qualitative methods can naturally represent the subtleties of this regional marine governance.

These considerations indicate that this thesis opened important research questions concerning the offshore grid, to be addressed through regulatory analysis and a simulation model representing governance constraints. Moreover, investigating these questions also furthers the use of simulation approaches to applied expansion planning and governance regulation.

Appendix A: Offshore transmission expansion pathways

Table A.1: Availability factors for renewable energy technologies

Snapshot	1	2	3
Solar PV	0.40	0.25	0.10
Onshore Wind	0.62	0.36	0.10
Offshore Wind	0.70	0.40	0.10
British and European continental hydropower	0.24	0.24	0.24
Scandinavian hydropower	0.42	0.42	0.42

(% of installed capacity)

Table A.2: Long-run marginal cost of generation technologies

	Gas	Coal	Lignite	Nuclear	Offshore Wind	Onshore Wind	PV	Hydropower
Total marginal cost (€/MWh)	52.63	43.70	42.70	18.00	16.88	9.60	8.55	8.18
Equivalent O&M and fuel cost (€/MWh)	44.63	25.20	25.20	18.00	16.88	9.60	8.55	8.18
CO_2 cost @ 20 €/tCO_2 (€/MWh)	8.00	18.50	17.50	0.00	0.00	0.00	0.00	0.00
Emission Factor (tCO_2/MWh)	0.400	0.925	0.875	0.00	0.00	0.00	0.00	0.00

Table A.3: Cable and terminal investment costs

	Cable Cost c_c	**Terminal Investment Cost c_t**		
Parameter	c_c	Onshore c_{on}	Wind Farm c_{owf}	Offshore Hub c_{hub}
	M€/MW.km	M€/MW		
Low		0.05	0.10	
Central	0.0004	0.10	0.30	0.20
High		0.15	0.50	

Table A.4: K_t rules according to terminal and link technology

Point-to-point links

	Radial	Farm-to-farm	Hub	Split	IC split	Radial split
Onshore	Sum	Sum	Sum	Sum	Sum	Sum
Offshore hub						
Offshore wind farm						

Multiterminal links

	Radial	Farm-to-farm	Hub	Split	IC split	Radial split
Onshore	Sum	Sum	Sum	Sum	Sum	Sum
Offshore hub	Null	Null	Null	Null	Null	Null
Offshore wind farm	Sum	Max	Sum	Max	Max	Max

Sum: K_t is equal to the total transmission capacity sum of all links connected to the node; Max: K_t equals the maximum transmission capacity among links connected to the node; Null: K_t is equal to zero

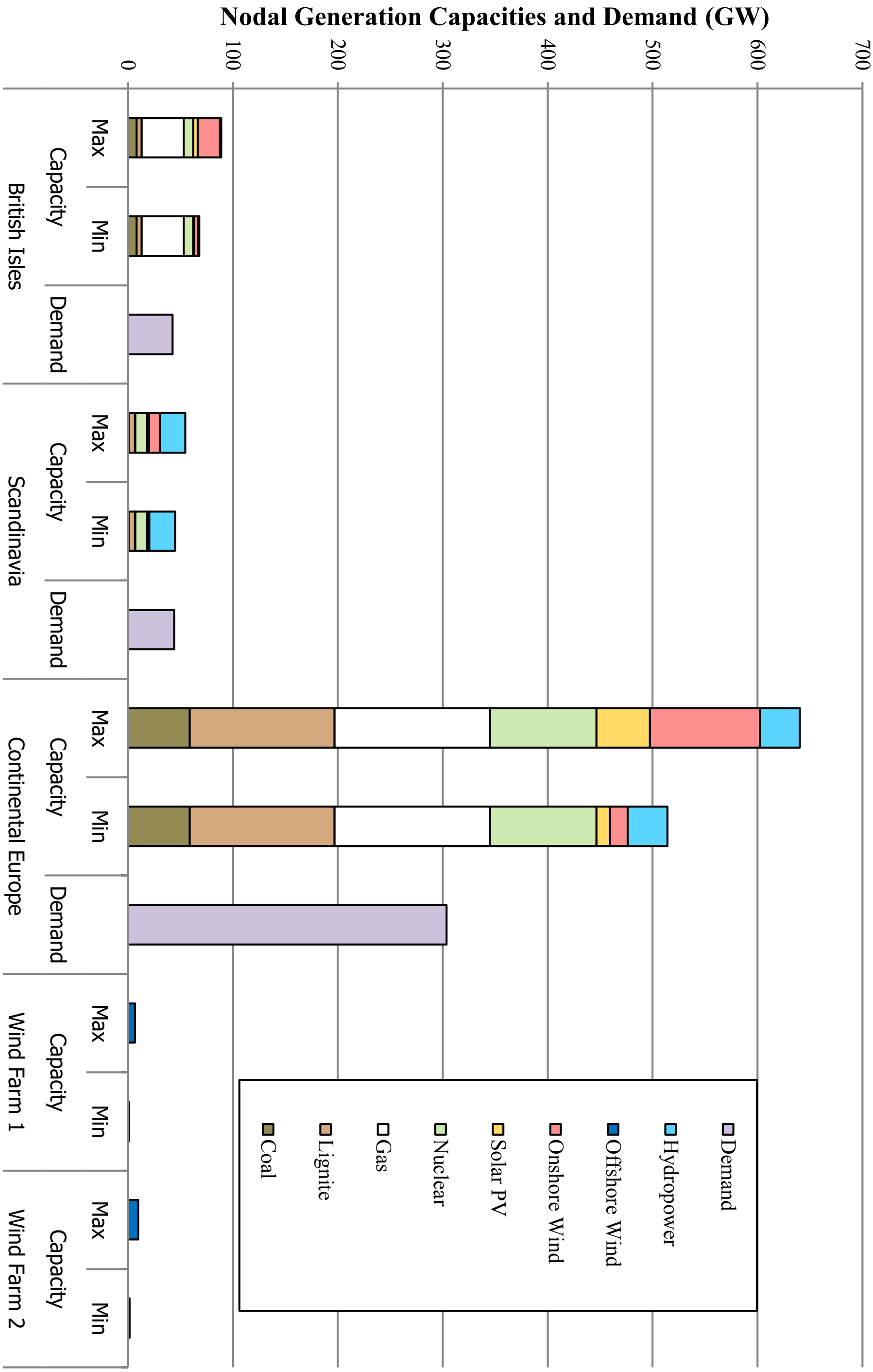

Figure A.1: Adjusted total nodal generation capacities

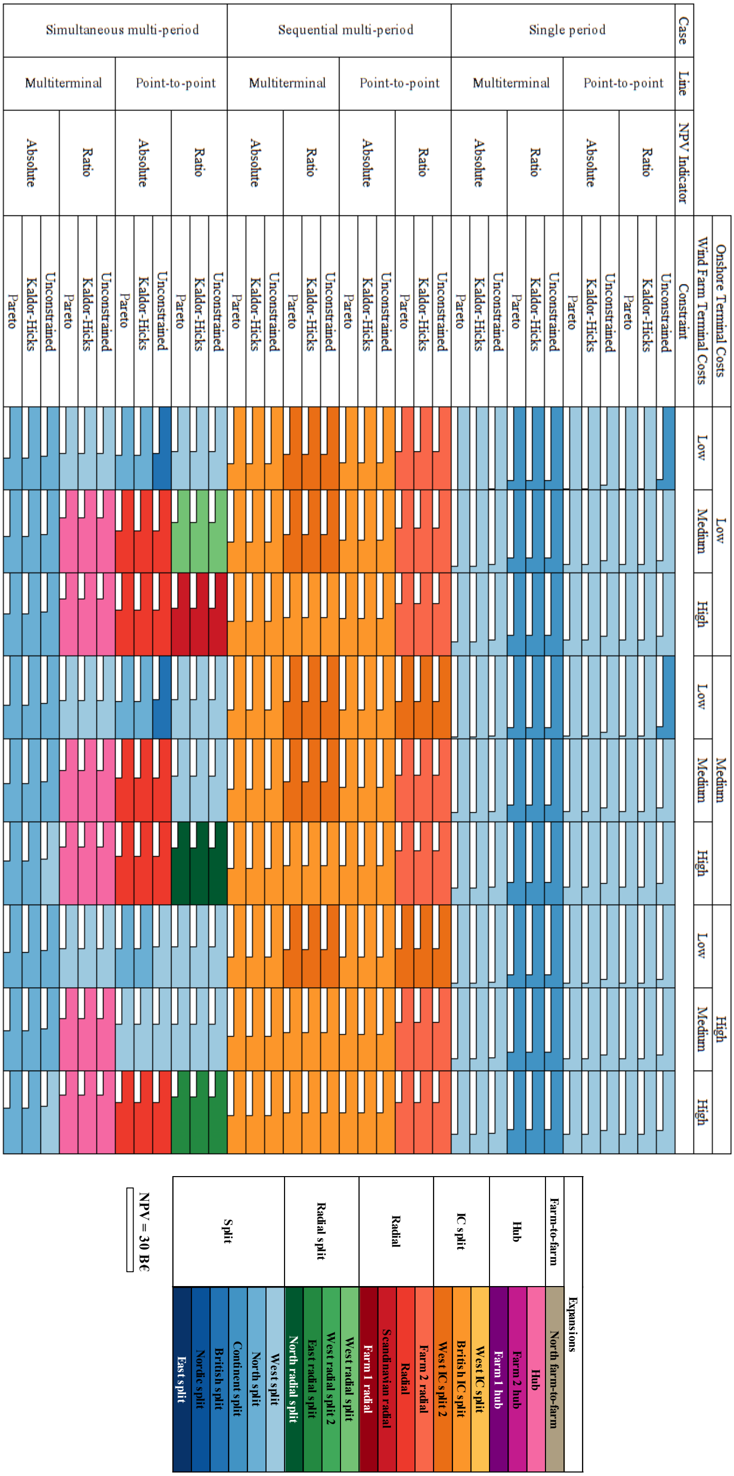

Figure A.2: First period expansion NPV_a and selected typology

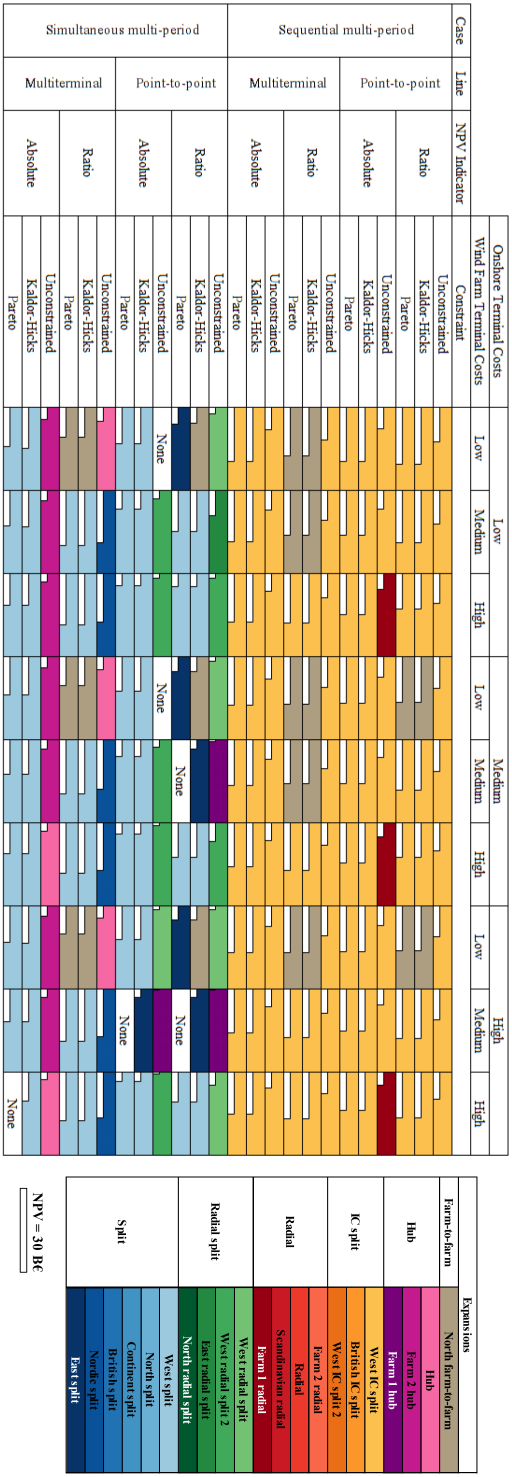

Figure A.3: Second period expansion NPV_a and selected typology

Appendix B: North Sea generation and transmission expansion pathways

B.1 Offshore Grid Exploratory Model formulation and description

Sets and indices

$n \in \mathrm{N}$	System nodes
$n \in \mathrm{N}_{nsc}$	$\forall\ nsc$, Nodes of country nsc, $N_{nsc} \subset \mathrm{N}$
$g \in \mathrm{G}$	Generators
$g \in \mathrm{G}^{\mathrm{EC}}$	Energy-constrained generators, $\mathrm{G}^{\mathrm{EC}} \subset \mathrm{G}$
$g \in \mathrm{G}^{\mathrm{ENS}}$	Load shedding generators, $\mathrm{G}^{\mathrm{ENS}} \subset \mathrm{G}$
$g \in \mathrm{G}^{H}$	Hydro generators, $\mathrm{G}^{H} \subset \mathrm{G}^{\mathrm{EC}}$
$g \in \mathrm{G}^{NSC}_{nsc}$	$\forall\ nsc$, generators of country nsc, $\mathrm{G}^{NSC}_{nsc} \subset \mathrm{G}$
$g \in \mathrm{G}^{\mathrm{OW}}$	Offshore wind clusters
$l \in \mathrm{L}$	Transmission lines
$l \in \mathrm{L}^{0}$	Existing transmission lines, $\mathrm{L}^{0} \subset \mathrm{L}$
$l \in \mathrm{L}^{CIL}$	Candidate integrated transmission lines, $\mathrm{L}^{CIL} \subset \mathrm{L}^{CL}$
$l \in \mathrm{L}^{CIL}_{nsc}$	$\forall\ nsc$, Candidate integrated transmission lines of country nsc, $\mathrm{L}^{CIL}_{nsc} \subset \mathrm{L}^{CIL}$
$l \in \mathrm{L}^{AC}$	HVAC transmission lines, $\mathrm{L}^{AC} \subset \mathrm{L}$
$l \in \mathrm{L}^{MTDC}$	Multiterminal HVDC transmission lines, $\mathrm{L}^{MTDC} \subset \mathrm{L}$
$l \in \mathrm{L}^{PTP}$	Point-to-point HVDC transmission lines, $\mathrm{L}^{PTP} \subset \mathrm{L}$
$l \in \mathrm{L}^{C}$	AC/DC converters, $\mathrm{L}^{C} \subset \mathrm{L}$
$nsc \in \mathrm{NSC}$	North Sea countries NSC = {BE, DE, DK, FR, GB, IE, NO, NL, SE}
$sn \in \mathrm{SN}$	Snapshots
$s \in \mathrm{S}$	Storage units
$s \in \mathrm{S}_{nsc}$	$\forall\ nsc$, storage units of country nsc, $\mathrm{S}_{nsc} \subset \mathrm{S}$

Parameters

$\lambda_{n,it}$	Nodal marginal price for node n, in current iteration it
$\overline{\mathrm{A}}^{G}_{\mathrm{g,sn}}$	Availability factor in [0,1] for generator g in snapshot sn
$\mathrm{B}^{L}_{l,n}$	Incidence matrix value for transmission line l and node n
$\mathrm{C}^{CL}_{n,l}$	Cost distribution matrix of candidate lines to nodes

$\mathrm{C}_{n,l}^{OW}$	Cost distribution matrix of offshore wind clusters to nodes
$\mathrm{D}_{\mathrm{n,sn}}$	Node demand at snapshot sn
ε^{T}	Penalty to minimize transmission flows
$\overline{\mathrm{E}}_{\mathrm{g}}$	Annual available energy for energy-constrained generator g
$\Phi_{\mathrm{s,sn}}$	Inflow for storage unit s at snapshot sn
$\overline{F}_{\mathrm{l}}$	Maximum transmission capacity for transmission line l
i_l	Starting node for transmission line l
j_l	End node for transmission line l
$\mathrm{K}_{\mathrm{l}}^{\mathrm{LI}}$	Annuitized, hour-equivalent investment cost of transmission line l
$\mathrm{K}_{\mathrm{g}}^{\mathrm{OWI}}$	Annuitized, hour-equivalent investment cost of offshore wind cluster g
$\mathrm{K}_{\mathrm{g}}^{\mathrm{G}}$	Operational marginal cost of generator g $\in \mathrm{G} - \mathrm{G}^{\mathrm{ENS}}$
$\mathrm{K}_{\mathrm{s}}^{\mathrm{S}}$	Storage cost of storage unit s
M^{F}	Disjunctive (big M) parameter for flow constraints
M_{ns}^{W}	Disjunctive (big M) parameter for welfare constraints for country nsc
M_{l}^{R}	Disjunctive (big M) parameter for the minimum investment ratio
$\overline{\mathrm{P}}_{\mathrm{s}}^{\mathrm{S}}$	Generation and storage capacity for storage unit s
$\overline{\mathrm{P}}_{\mathrm{g}}^{G}$	Generation capacity for generator g ∈ G - G^{OW}
$\overline{\mathrm{P}}_{\mathrm{g}}^{0}$	Starting generation capacity for offshore wind cluster g $\in \mathrm{G}^{\mathrm{OW}}$
$\overline{\mathrm{P}}\%_{\mathrm{g}}^{H}$	Maximum generation % per snapshot for hydro generator g
$\underline{\mathrm{P}}\%_{\mathrm{g}}^{H}$	Minimum generation % per snapshot for hydro generator g
$\underline{R_l}$	Minimum investment ratio for candidate line l
SH_{s}	Maximum storage hours for storage unit s
$VOLL$	Value of lost load for load shedding generators
W_{sn}	Probability of snapshot sn, $\sum \mathrm{W}_{sn} = 1$
W_{nsc}^{0}	Base welfare for country nsc
$\overline{ID}^{CIL}$	Limit for integrated transmission lines investment per node
X_{l}	Reactance of transmission line l ∈ L^{AC}
R_{l}	Resistance of transmission line l ∈ L^{DC}

Variables

$\mathrm{p}_{\mathrm{g,sn}}$	Generation of generator g at snapshot sn
$\mathrm{p}_{s,\mathrm{sn}}$	Generation of storage unit s at snapshot sn
$s_{s,\mathrm{sn}}$	Storage of storage unit s at snapshot sn
$soc_{s,\mathrm{sn}}$	State of charge of storage unit s at snapshot sn
$f_{l,\mathrm{sn}}$	Flow of transmission line l at snapshot sn
$\lvert f_{l,\mathrm{sn}} \rvert$	Absolute flow of transmission line l at snapshot sn
$\overline{f}_{\mathrm{l}}^{C}$	Maximum transmission capacity of candidate converter l
$\overline{\mathrm{p}}_{\mathrm{g}}^{OW}$	Generation capacity of offshore wind cluster g ∈ G^{OW}
$\theta_{\mathrm{n,sn}}$	Node n voltage angle at snapshot sn
$\mathrm{v}_{\mathrm{n,sn}}$	Node n voltage magnitude at snapshot sn
id_{l}	Binary investment decision for candidate line l
r_{l}	Investment ratio for candidate line l
c_{nsc}	Binary cooperation for country nsc

Equations and expressions

$$\min \textstyle\sum_{sn} \sum_{g \in \mathrm{G}-\mathrm{G}^{\mathrm{ENS}}} \mathrm{W}_{sn} * \left(\mathrm{K}_{\mathrm{g}}^{\mathrm{G}} * \mathrm{p}_{\mathrm{g,sn}}\right) + \sum_{sn} \sum_{g \in \mathrm{G}^{\mathrm{ENS}}} \mathrm{W}_{sn} * \left(\mathrm{VOLL} * \mathrm{p}_{\mathrm{g,sn}}\right) + \sum_{sn} \sum_{\mathrm{l} \in \mathrm{L}-\mathrm{L}^{C}} \mathrm{W}_{sn} * \varepsilon^{\mathrm{T}} * \lvert f_{l,\mathrm{sn}} \rvert + \sum_{g \in \mathrm{G}^{\mathrm{OW}}} \mathrm{K}_{\mathrm{g}}^{\mathrm{OWI}} * \left(\overline{\mathrm{p}}_{\mathrm{g}}^{OW} - \overline{\mathrm{P}}_{\mathrm{g}}^{0}\right) + \sum_{l \in \mathrm{L}^{CL}-\mathrm{L}^{C}} \mathrm{K}_{\mathrm{l}}^{\mathrm{LI}} * \overline{\mathrm{F}}_{\mathrm{l}} * r_{l} + \sum_{l \in \mathrm{L}^{CL} \cap \mathrm{L}^{C}} \mathrm{K}_{\mathrm{l}}^{\mathrm{LI}} * \overline{\mathrm{f}}_{\mathrm{l}}^{C} \qquad (1)$$

(1) is the investment and operation costs minimization objective function. Operation costs are composed of generation dispatch costs and load curtailment costs, while investment costs arise from investments in offshore wind farms and offshore transmission lines and converters. Power transmission is minimized through the ε^{T} penalty to favor local node dispatch (which affects the welfare distributions between countries) in the presence of equal-marginal cost generators.

subject to:

$$\mathrm{p}_{\mathrm{g,sn}} + \mathrm{p}_{s,\mathrm{sn}} - s_{s,\mathrm{sn}} + \textstyle\sum_{l} \mathrm{B}_{l,n}^{L} * f_{l,\mathrm{sn}} = \mathrm{D}_{\mathrm{n,sn}} \qquad \forall \text{ n,sn} : \lambda_{b,it} \qquad (2)$$

(2) is the nodal balance constraint, stating that the net generation and storage dispatch plus the net incoming flows must equal the demand for each node.

$$\frac{\theta_{j_l,\mathrm{sn}} - \theta_{i_l,\mathrm{sn}}}{\mathrm{x}_{\mathrm{l}}} = f_{l,\mathrm{sn}} \qquad \forall \text{ l} \in \mathrm{L}^{0} \cap \mathrm{L}^{AC}, \text{ sn} \qquad (3)$$

$$\frac{\mathrm{v}_{j_l,\mathrm{sn}} - \mathrm{v}_{i_l,\mathrm{sn}}}{\mathrm{r}_{\mathrm{l}}} = f_{l,\mathrm{sn}} \qquad \forall \text{ l} \in \mathrm{L}^{0} \cap \mathrm{L}^{MTDC}, \text{ sn} \qquad (4)$$

$$f_{l,\mathrm{sn}} \leq \frac{\theta_{j_l,\mathrm{sn}} - \theta_{i_l,\mathrm{sn}}}{\mathrm{X}_{\mathrm{l}}} + M * (id_{l} - 1) \qquad \forall \text{ l} \in \mathrm{L}^{CL} \cap \mathrm{L}^{AC}, \text{ sn} \qquad \text{(5a-b)}$$

$$f_{l,\mathrm{sn}} \geq \frac{\theta_{j_l,\mathrm{sn}}-\theta_{i_l,\mathrm{sn}}}{\mathrm{X}_\mathrm{l}} - M * (id_l \ -1)$$

$$f_{l,\mathrm{sn}} \leq \frac{\mathrm{v}_{j_l,\mathrm{sn}}-v_{i_l,\mathrm{sn}}}{R_\mathrm{l}} + M * (id_l \ -1) \qquad \forall\ \mathrm{l} \in \mathrm{L}^{CL} \cap \mathrm{L}^{MTDC}, \mathrm{sn} \qquad (6a\text{-}b)$$

$$f_{l,\mathrm{sn}} \geq \frac{v_{j_l,\mathrm{sn}}-v_{i_l,\mathrm{sn}}}{\mathrm{R}_\mathrm{l}} - M * (id_l \ -1)$$

(3-4) enforce the linearized power flow equations for existing transmission HVAC and multiterminal HVDC lines respectively, while (5a-b) and (6-a-b) enforce it only for selected candidate HVAC and multiterminal HVDC lines thanks to the disjunctive big M parameter.

$$-\overline{\mathrm{F}}_\mathrm{l} \ \leq f_{l,\mathrm{sn}} \leq \overline{\mathrm{F}}_\mathrm{l} \qquad \forall\ \mathrm{l} \in \mathrm{L}^0, \mathrm{sn} \qquad (7)$$

$$-\overline{\mathrm{F}}_\mathrm{l} \ * r_l \ \leq f_{l,\mathrm{sn}} \leq \overline{\mathrm{F}}_\mathrm{l} \ * r_l \qquad \forall\ \mathrm{l} \in (\mathrm{L}^{CL} - \mathrm{L}^{C}), \mathrm{sn} \qquad (8)$$

$$-\overline{f}_\mathrm{l}^{C} \leq f_{l,\mathrm{sn}} \leq \overline{f}_\mathrm{l}^{C} \qquad \forall\ \mathrm{l} \in (\mathrm{L}^{CL} \cap \mathrm{L}^{C}), \mathrm{sn} \qquad (9)$$

$$r_l \ + \mathrm{M}_l^R * (1 - id_l \ ) \geq \underline{R_l} \qquad \forall\ \mathrm{l} \in \mathrm{L}^{CL}, \mathrm{sn} \qquad (10)$$

$$r_l \ \leq id_l \qquad \forall\ \mathrm{l} \in \mathrm{L}^{CL}, \mathrm{sn} \qquad (11)$$

The binary variable id_l represents the investment decision for each candidate transmission line, while r_l is the line investment ratio (ranging from 0 to 100% of the $\overline{\mathrm{F}}_\mathrm{l}$ maximum transmission capacity). Thus (7-9) enforce the maximum transmission capacities for existing lines and converters, candidate lines and candidate converters, respectively. (10) establishes a minimum investment ratio when $id_l \ = 1$, while (11) enforces that $\mathrm{r}_\mathrm{l} \ = 0$ when the candidate line is not invested in. While transmission investment variables are binary to model integrated governance constraints, generation investment is modelled with the continuous variable $\overline{\mathrm{p}}_\mathrm{g}^{OW}$.

$$\mathrm{p}_{\mathrm{g,sn}} \leq \overline{\mathrm{P}}_\mathrm{g}^{G} * \overline{\mathrm{A}}_{\mathrm{g,sn}}^{G} \qquad \forall\ \mathrm{g} \in \mathrm{G}\text{-}\mathrm{G}^{\mathrm{OW}}, \mathrm{sn} \qquad (12)$$

$$\mathrm{p}_{\mathrm{g,sn}} \leq \overline{\mathrm{p}}_\mathrm{g}^{OW} * \overline{\mathrm{A}}_{\mathrm{g,sn}}^{G} \qquad \forall\ \mathrm{g} \in \mathrm{G}^{\mathrm{OW}}, \mathrm{sn} \qquad (13)$$

$$\mathrm{p}_{s,\mathrm{sn}} \leq \overline{P}_s^{S} \qquad \forall\ \mathrm{s}, \mathrm{sn} \qquad (14)$$

$$\textstyle\sum_{sn} \mathrm{p}_{\mathrm{g,sn}} \leq \overline{\mathrm{E}}_\mathrm{g} \qquad \forall\ \mathrm{g} \in \mathrm{G}^{\mathrm{EC}} \qquad (15)$$

$$\underline{\mathrm{P\%}}_\mathrm{g}^{H} * \overline{\mathrm{P}}_\mathrm{g}^{G} \leq \mathrm{p}_{\mathrm{g,sn}} \leq \overline{\mathrm{P\%}}_\mathrm{g}^{H} * \overline{\mathrm{P}}_\mathrm{g}^{G} \qquad \forall\ \mathrm{g} \in \mathrm{G}^{H}, \mathrm{sn} \qquad (16)$$

(12-14) limit the generation to the maximum capacity of each onshore and offshore wind generator and storage unit, respectively, taking into account availability factors. For energy-constrained generators (15) limits the annual total generation to the available energy, while (16) establishes minimum and maximum generation percentages to hydro generators to better model real flow constraints for hydropower.

$$\mathrm{s}_{s,\mathrm{sn}} \leq \overline{P}_s^{S} \qquad \forall\ \mathrm{s}, \mathrm{sn} \qquad (17)$$

$$\mathrm{soc}_{\mathrm{s,sn}} - \mathrm{soc}_{\mathrm{s,sn-1}} - \mathrm{p}_{\mathrm{s,sn}} + \mu_{\mathrm{sn}} * \mathrm{s}_{\mathrm{s,sn}} + \Phi_{\mathrm{s,sn}} = 0 \qquad \forall\ \mathrm{s}, \mathrm{sn} \qquad (18)$$

$$\mathrm{soc}_{\mathrm{s,sn}} \leq \mathrm{SH}_\mathrm{s} \ * \overline{P}_s^{S} \qquad \forall\ \mathrm{s}, \mathrm{sn} \qquad (19)$$

(17) limits the maximum storage for each storage unit and snapshot. (18) enforces the state of charge constraint for each storage unit between two sequential snapshots considering inflows and the net dispatch of the unit, while (19) limits the state of charge according to the energy reservoir size.

Integrated governance constraints

$$\sum_{l\,\in\,\mathrm{L}^{CIL}} \left|\mathrm{B}_{l,n}^{L}\right| * id_l \;\le \overline{ID}^{CIL} \qquad \forall\ \mathrm{n} \qquad (20)$$

Given the identification in Section 1.1 of the costs and benefits distribution and coordination complexity as major governance barriers to an integrated grid, these barriers are modelled separately as constraints in the myopic model. The integration constraint (20) limits the number of integrated lines built for any node in a given expansion period to a certain limit $\overline{ID}^{CIL} \in \{0,1,\infty\}$.

$$\sum_{sn}\sum_{g\in \mathrm{G}_{nsc}^{NSC}} \mathrm{W}_{sn} * \mathrm{p}_{\mathrm{g,sn}} * \left(\lambda_{n,it-1} - \mathrm{K}_{\mathrm{g}}^{\mathrm{G}}\right) + \sum_{sn}\sum_{s\in \mathrm{S}_{nsc}^{NSC}} \mathrm{W}_{sn} * p_{\mathrm{s,sn}} * \lambda_{n,it-1} - \sum_{sn}\sum_{s\in \mathrm{S}_{nsc}^{NSC}} \mathrm{W}_{sn} * \mathrm{s}_{\mathrm{s,sn}} * \lambda_{n,it-1} + \sum_{sn}\sum_{n\in \mathrm{N}_{nsc}}\sum_{l} \mathrm{W}_{sn} * \mathrm{C}_{n,l}^{CL} * \left|\mathrm{B}_{l,n}^{L}\right| * f_{l,\mathrm{sn}} * \left(\lambda_{j_l,it-1} - \lambda_{i_l,it-1}\right) - \sum_{sn}\sum_{n\in \mathrm{N}_{nsc}} \mathrm{W}_{sn} * \lambda_{n,it-1} * \mathrm{D}_{\mathrm{n,sn}} - \sum_{n\in \mathrm{N}_{nsc}}\sum_{l\,\in\,\mathrm{L}^{CL}-\mathrm{L}^{C}} \mathrm{C}_{n,l}^{CL} * \left|\mathrm{B}_{l,n}^{L}\right| * \mathrm{K}_{\mathrm{l}}^{\mathrm{LI}} * \overline{\mathrm{F}}_{\mathrm{l}} * r_l - \sum_{n\in \mathrm{N}_{nsc}}\sum_{l\,\in\,\mathrm{L}^{CL}\cap\mathrm{L}^{C}} \left|\mathrm{B}_{l,n}^{L}\right| * \mathrm{K}_{\mathrm{l}}^{\mathrm{LI}} * \overline{\mathrm{f}}_{\mathrm{l}}^{C} - \sum_{g\,\in\,\mathrm{G}^{\mathrm{OW}}\cap\mathrm{G}_{nsc}} \mathrm{C}_{n,g}^{OW} * \mathrm{K}_{\mathrm{g}}^{\mathrm{OWI}} * \left(\overline{\mathrm{p}}_{\mathrm{g}}^{OW} - \overline{\mathrm{P}}_{\mathrm{g}}^{0}\right) - \mathrm{W}_{nsc}^{0} - \mathrm{M}_{nsc}^{W} * c_{nsc} \ge -\mathrm{M}_{nsc}^{W} \qquad \forall\ nsc \qquad (21)$$

The coordination variable is used to implement the integrated governance constraints. Therefore, (21) represents the Pareto welfare constraint, a veto of a North Sea country to integrated lines. When constraint (21) is active (i.e. when c_{ns} = 1), any country whose welfare decreases relative to the base welfare W_{ns}^{0} does not build any integrated lines [21]. Since nodal prices $\lambda_{n,it}$ is the dual of equation (2) the solution of the problem is iterated, updating constraint (21) with prices $\lambda_{n,it-1}$ from the previous iteration until the stop criterion is met. The stop criterion is met when constraint (21) is satisfied with the new prices $\lambda_{n,it}$ and the objective function (1) value remained constant within the optimality gap tolerance.

$$\left|f_{l,\mathrm{sn}}\right| \ge f_{l,\mathrm{sn}} \qquad \forall\ \mathrm{l} \in \mathrm{L} - \mathrm{L}^{C}\text{ , sn} \qquad (22a\text{-}b)$$

$$\left|f_{l,\mathrm{sn}}\right| \ge -f_{l,\mathrm{sn}}$$

$$c_{nsc} \le \sum_{l\in \mathrm{L}_{ns}^{CIL}} id_l \;\le card(L) * c_{nsc} \qquad \forall\ nsc \qquad (23)$$

For the auxiliary variables, (22a-b) guarantees that $\left|f_{l,\mathrm{sn}}\right|$ is the absolute value of $f_{l,\mathrm{sn}}$. (23) implements the coordination binary variable c_{ns} which indicates whether each North Sea country has built integrated lines. Integrated lines are lines which connect two offshore wind farms or that connect an offshore wind farm directly to an onshore node belonging to another country. In contrast, conventional lines interconnect onshore nodes or offshore wind farms to national onshore nodes.

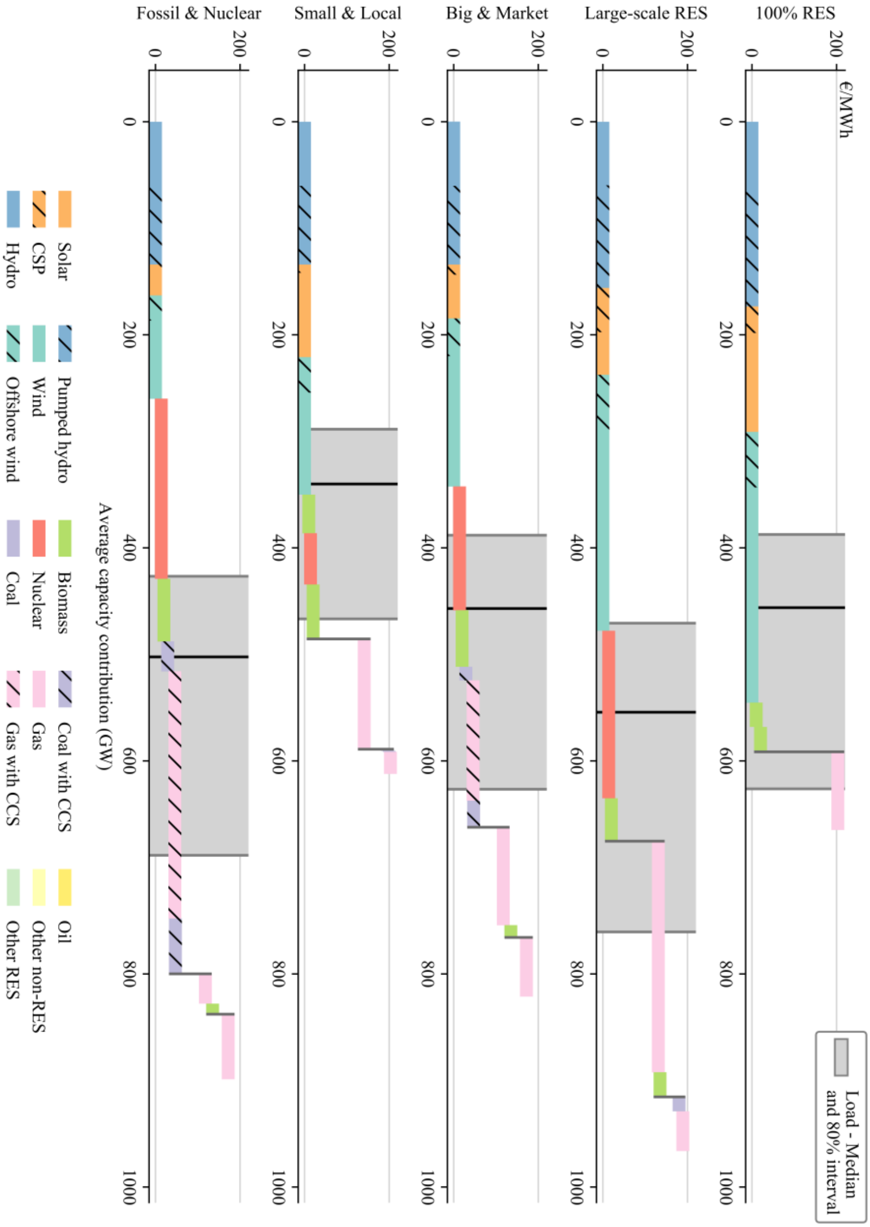

Figure B.1: 2050 merit order curve with investments (unconstrained case)

Table B.5: Offshore grid expansion pathways measures

		B€$_{2030}$		B€$_{2030}$/year						GW	TW·km		
		Investments			Surpluses								
Scenario	**Governance constraint**	**Offshore wind**	**Transmission**	**Net benefits**	**Consumers**	**Congestion rent**	**Conventional producers**	**Offshore producers**	**Renewable producers**	**Offshore wind capacity**	**HVAC**	**Multiterminal HVDC**	**Point-to-point HVDC**
100% RES	Unconstrained	170.7	55.7	24.44	316.2	-28.3	-127.8	0.1	-124.7	114.9	5.98	4.74	13.36
	Pareto welfare	175.4	61.5	24.30	321.0	-28.6	-129.8	-0.2	-126.7	114.9	4.98	10.81	11.75
	Complex integration	173.6	57.9	24.40	314.2	-27.8	-126.8	0.3	-124.3	114.9	3.50	9.53	10.97
	Disintegrated planning	174.0	63.7	24.30	323.8	-28.3	-131.3	-0.9	-127.5	114.9	6.89	16.06	6.01
Large-scale RES	Unconstrained	172.4	48.7	13.60	57.9	-5.7	-17.4	7.9	-18.3	114.3	4.86	9.31	5.38
	Pareto welfare	172.6	60.2	13.32	58.7	-6.5	-17.2	8.1	-18.6	113.1	3.69	12.86	7.58
	Complex integration	177.1	50.1	13.30	60.2	-4.5	-19.8	8.3	-20.0	114.4	4.78	8.04	6.57
	Disintegrated planning	170.1	57.1	13.39	58.2	-6.9	-16.5	7.7	-18.1	114.9	6.23	12.40	4.69
Big & Market	Unconstrained	103.5	30.5	3.24	22.4	-0.9	-11.4	4.4	-4.9	78.7	4.57	6.38	0.65
	Pareto welfare	113.7	34.6	2.89	23.8	-0.4	-12.3	4.4	-5.5	84.1	3.30	6.66	2.15
	Complex integration	117.9	31.5	3.24	24.7	-0.4	-12.8	4.5	-5.6	86.1	4.21	3.90	2.67
	Disintegrated planning	101.3	30.7	2.85	21.9	-0.3	-10.9	3.7	-5.2	77.3	4.84	6.51	0.00
Small & Local	Unconstrained	88.2	33.3	1.38	54.5	-1.7	-30.6	1.8	-16.7	72.4	2.11	6.02	3.39
	Pareto welfare	67.1	27.7	1.37	49.0	-1.8	-27.7	1.2	-14.8	64.4	2.09	5.52	2.34
	Complex integration	108.1	31.9	0.90	58.6	-1.2	-32.8	1.4	-18.3	86.3	3.41	5.71	4.17
	Disintegrated planning	79.5	38.2	1.21	51.8	-0.9	-29.4	0.8	-15.4	68.8	4.54	4.09	5.40
Fossil & Nuclear	Unconstrained	58.9	18.9	1.46	2.8	-0.7	1.2	2.7	-0.8	51.5	1.93	0.29	4.32
	Pareto welfare	59.4	21.9	1.34	0.0	-0.6	3.6	2.5	-0.4	54.2	3.14	4.27	0.36
	Complex integration	46.5	23.3	1.23	0.4	-0.6	3.0	2.1	-0.3	46.6	2.95	2.68	3.82
	Disintegrated planning	26.2	19.8	1.35	-4.0	-0.8	7.0	1.1	0.3	36.4	3.04	4.33	0.00

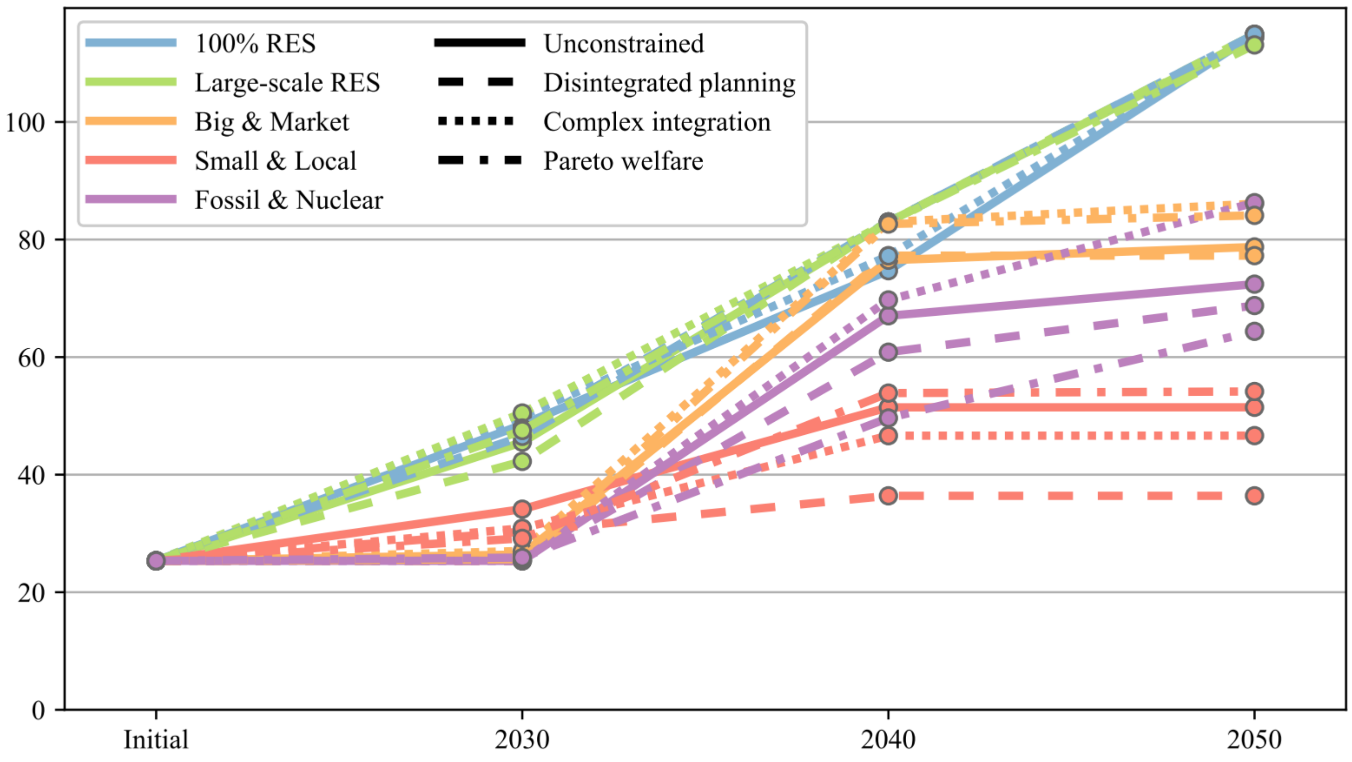

Figure B.2: Offshore wind installed capacity (GW)

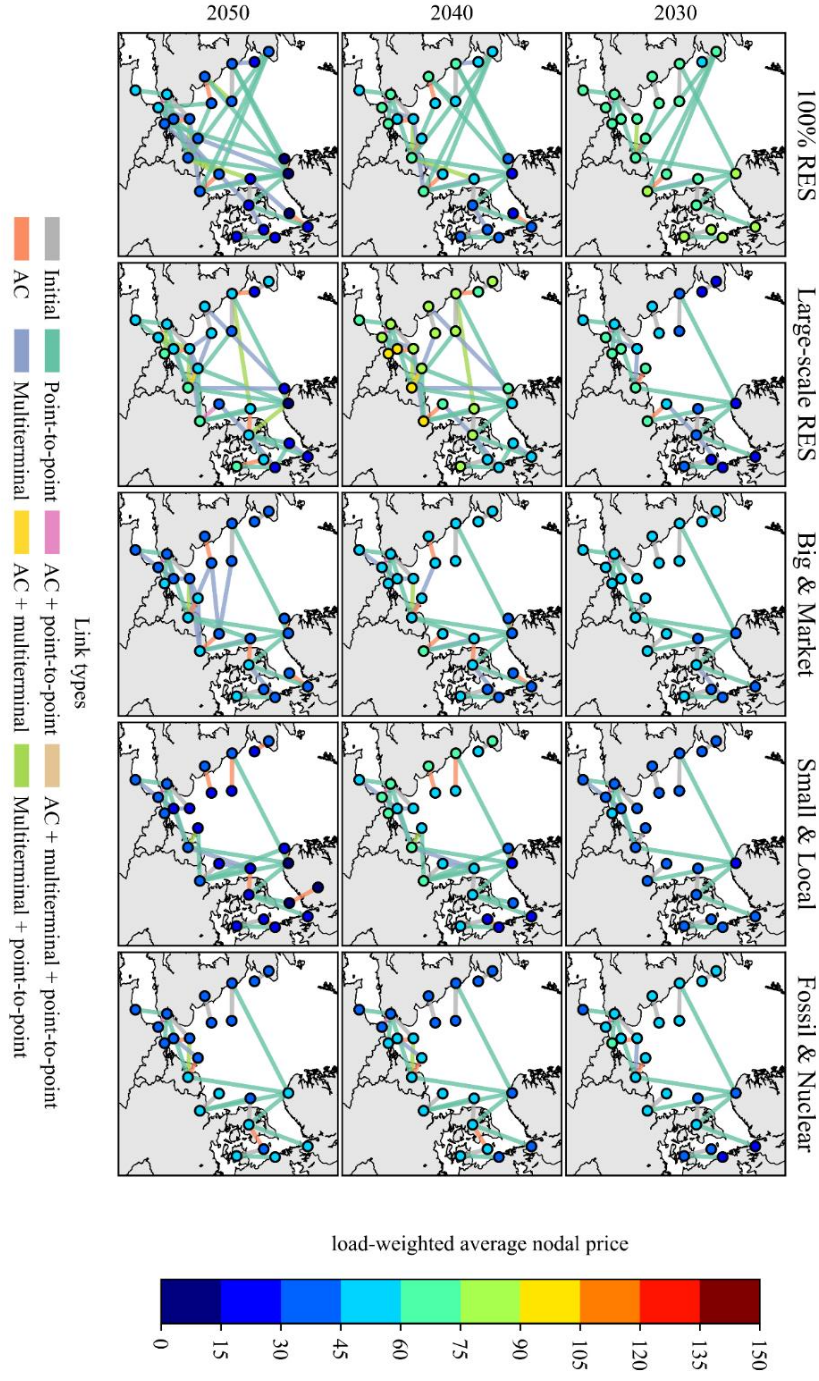

Figure B.3: Unconstrained expansion pathways for the offshore grid

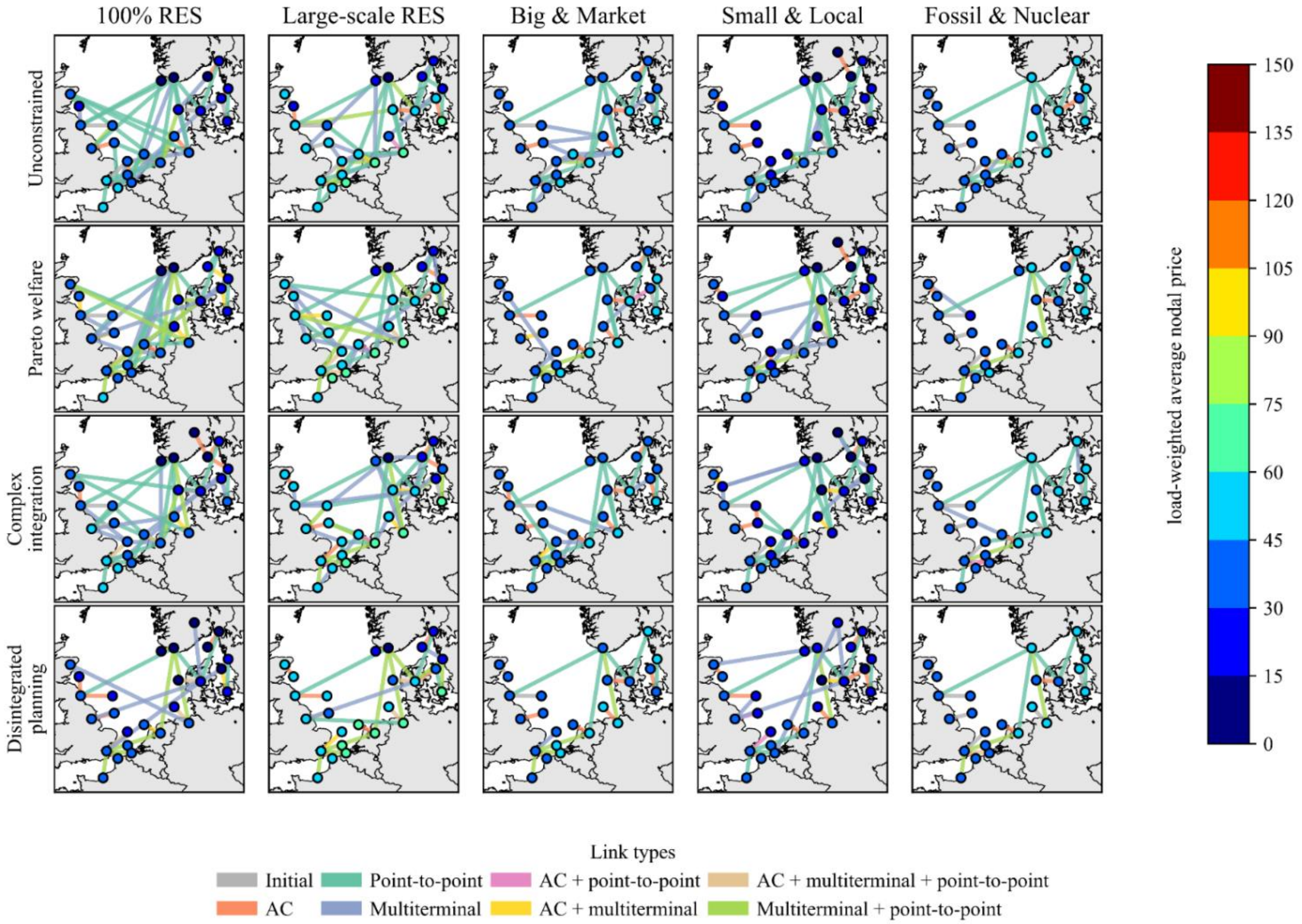

Figure B.4: 2050 offshore grid for all scenarios and governance constraints

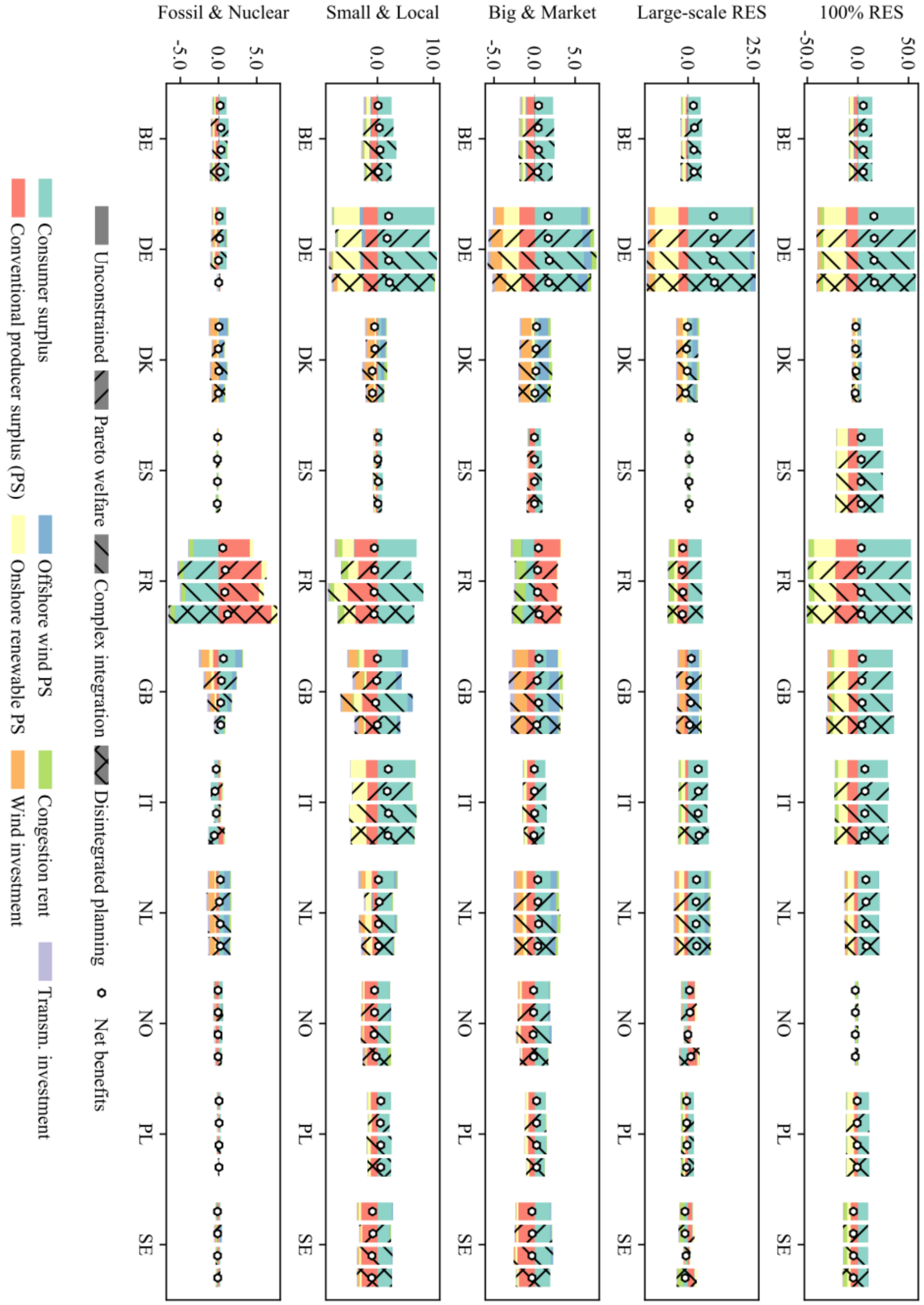

Figure B.5: Annualized costs and benefits (B€/year)

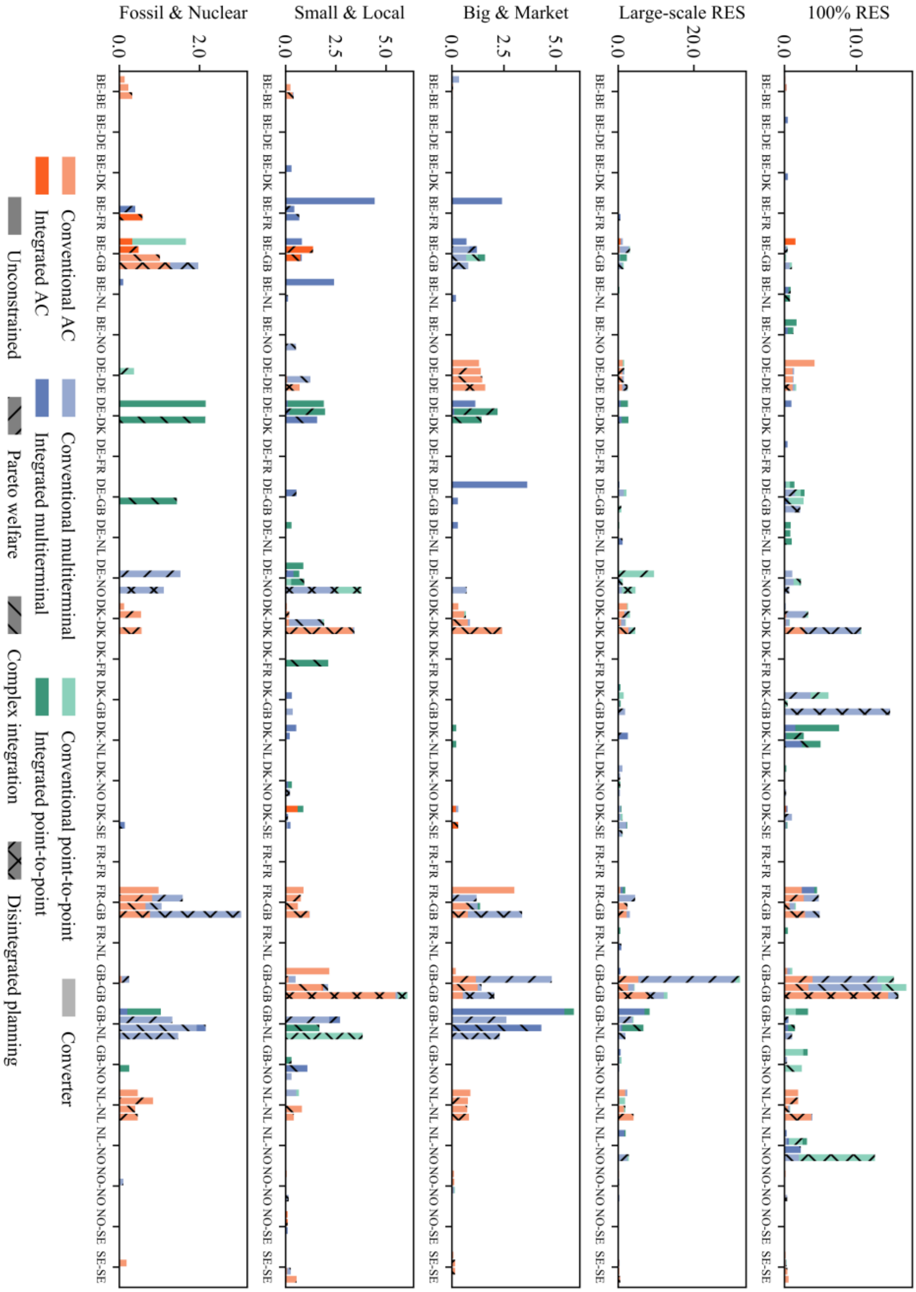

Figure B.6: Transmission corridors and technologies (TW·km)

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Curriculum Vitae

João Gorenstein Dedecca was born on the 29th of October 1985 in Campinas, Brazil, where he lived most of his childhood. In 2001 João started his studies in the Technical High School of Campinas (Cotuca), where he followed the electro-technical course, from which he graduated in 2004.

In 2004 João started the Electrical Engineering B.Sc. at the Campinas State University (Unicamp). At Unicamp João conducted undergraduate research on algorithms for the auralization of room acoustics and obtained his B.Sc. diploma in 2010 with a Honors Thesis on the Brazilian wind power sector. During his Bachelor studies João followed an exchange program at the École Centrale de Lyon (France) in the Energy and Research & Development Engineering tracks. During his exchange he conducted an internship at the Global Research Center of Alstom Hydro, investigating rotor-stator dynamic interactions in hydraulic turbines.

João then joined the Energy Systems Planning master degree program of Unicamp, graduating in 2012 with a thesis on the barriers to the development of onshore wind power in Brazil and Argentina. In the same year João was selected for the Operations Management Leadership Program (OMLP) of General Electric (GE). At the OMLP João concluded four rotations in various areas of supply chain management, in the Energy and Healthcare businesses of GE in Brazil and Argentina. Following his OMLP graduation in 2013, he worked as an advanced manufacturing engineer at GE's rotating machines plant in Campinas.

In 2014 João joined the Erasmus Mundus Joint Doctorate on Sustainable Energy Technologies and Strategies (SETS) program. He then began investigating an economic and regulatory framework for the North Seas offshore grid at the Technology, Policy and Management Faculty of the Delft University of Technology. As part of the SETS doctorate, he was a visiting researcher at the Institute for Research in Technology (IIT) of the Comillas Pontifical University (Spain). During his doctorate, João authored several scientific articles on offshore wind power and transmission. He also organized workshops on energy systems modeling, supervised an M.Sc. thesis on the cost-benefit analysis of offshore power transmission, and co-organized energy research seminars.

In 2018 João joined Trinomics, an economic policy consultancy active in the fields of energy, environment and climate change.

Propositions

accompanying the dissertation

Expansion Governance of the Integrated North Seas Offshore Grid

by

João GORENSTEIN DEDECCA

1. A literature review is a reverse Pandora's box: a gift disguised as a curse
2. Choosing between modeling approaches for governance studies is a false dilemma
3. Even when used by no one else, open-source models and data lead to better studies than closed ones
4. The non-monetary benefits of an integrated offshore grid surpass the monetary ones
5. Hippocrates could not have composed his oath for policy makers
6. Project development for the integrated offshore grid has lower inertia than European laws
7. The failure to develop an integrated offshore grid will not prove its infeasibility
8. The governance of the integrated offshore grid is easier than translating 'navegar é preciso, viver não é preciso' to English
9. Navigating a Ph.D. research is necessary, but not accurate
10. Models are like people: imperfect, but you can always learn something from them

These propositions are regarded as opposable and
defendable, and have been approved as such
by the promotor prof. dr. ir. P.M. Herder and
by the promotor dr. ir. R.A. Hakvoort

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