Offshore Energy Hubs as an Emerging Concept
Sector Integration at Sea

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Supervisors: Tooraj Jamasb, Ruud Egging-Bratseth, Dogan Keles

Copenhagen, September 2022

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In liebevoller Erinnerung an
meine Großmutter Leonore.

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—Alexandra, September 2022

Man muss mehrere Vorbilder haben,
um nicht eine Parodie eines einzelnen zu werden.
— Erich Kästner.

Summary

Offshore energy hubs (OEHs), also often called energy islands, are discussed as becoming a key component of the energy transition in the Nordic and Baltic region and for Western and Central Europe. The idea involves the construction of production and conversion hubs far out at sea, where the wind energy potential is very high. Following the several European initiatives' visions (see North Sea Wind Power Hub, 2021) and a decision by the Danish Parliament (see Energistyrelsen, 2021), the idea is to create an artificial hub in European waters at a central location in areas of high renewable energy production—mainly offshore wind. OEHs are a new concept in the energy sector, and there is not yet extensive expertise and knowledge about them. Key questions surround optimal design, technology mix and connectivity, regulation, market design, and business models. This thesis develops three articles to answer two main research questions to contribute to the discussion on OEHs: (1) What are the main technological, environmental, economic, and societal drivers and challenges for the development of offshore energy hubs, and what is their impact on offshore electrolysis?, and (2) how do system configuration and market design influence the value of electrolysis on offshore energy hubs?

The first article, *Risks, Strategies, and Benefits of Offshore Energy Hubs*, develops a survey scheme inspired by multi-criteria analysis to assess the main drivers in the development of OEHs. I propose a definition, present the scheme, and conduct a survey based on the scheme for the case of the North Sea offshore energy infrastructure. Applying the suggested survey method to the context of the North Sea, I identify five trade-offs to be considered. The significance of the environmental benefits is strongly linked to the choice of materials and designs; changes to current assumptions may flip the system's benefits and turn the project into a series of sunk investments; coordinated and integrated planning is key to boosting the project's efficiency; offshore energy infrastructure presents a techno-

logical solution to energy system decarbonisation and needs to touch base with societal desires and behavioural solutions; and OEHs are currently standalone solutions with no competitors, which makes their benefits impossible to compare.

In the second paper, *How to Connect Energy Islands?*, we investigate the trade-offs between integrating OEHs via electricity and hydrogen infrastructures. We set up a combined capacity expansion and electricity dispatch model to assess the role of electrolysers and electricity cables in the availability of renewable energy from the islands. We find that the electricity system benefits from significant interconnection through the OEHs and offshore wind farms. In a scenario analysis, when electrolysers are built onshore, offshore electrolysis plays a smaller role. The energy system infrastructure offshore converges towards a meshed offshore grid and an OEH with a large electrolyser capacity. We observe that there is a chance for nuclear power and biomass to be used as fuel for electrolysers rather than offshore wind. Lastly, the capacity investments in electrolysers are very sensitive to hydrogen price but less to carbon price changes.

In a subsequent study, *Electrolysis as a Flexibility Resource on Energy Islands*, we discuss the operational role of electrolysers on an OEH. For OEHs currently under consideration in the North and Baltic Seas, we assess the potential flexibility contribution of the electrolyser and then analyse different market integration strategies of the islands. We align the market integration of the OEH to the current debate and compare the case of a single offshore bidding zone to one in which the OEH is integrated into a home market zone. Offshore wind energy is subject to fluctuations, and flexibility resources must compensate for those by selling or buying additional electricity in the respective market sequences—that is, intraday and balancing markets. To contribute to the debate about electrolysers as a flexible resource and how the combination of fluctuating wind energy and electrolysers can be integrated into the market, we develop a two-stage stochastic optimisation model to find a cost-efficient dispatch for an integrated day-ahead and balancing electricity market. We find that electrolysers on OEHs will run at low capacity factors and provide flexibility in 25 %–30 % of their run time. In addition, offshore electrolysers purchase electricity at slightly higher average costs in an offshore bidding zone while having higher capacity factors than the home

zone market. We conclude that policies for combining offshore wind with electrolysers on an OEH must consider the value of flexibility resources offshore and possible mechanisms to allow economic support.

The findings of the three articles summarise in answers to the research questions. OEHs are likely to evolve within or as part of a meshed grid and can deliver an environment for competitive hydrogen production. The hubs' specific designs are not yet defined, but first results point towards the hubs becoming homes for several technologies. The remote location makes the OEHs especially attractive for large hydrogen production, which in our analyses proves to be their main purpose; current technology costs are not competitive enough yet for flexibility provisions. Establishing OEHs and bidding zone configurations, and integrating sector coupling into economic frameworks for electricity markets, could be crucial for the project to deliver improvements to the energy system transformation.

Keywords: energy islands, energy system modelling, electrolysis, hydrogen, flexibility in renewable energy systems, offshore bidding zones, offshore grid, offshore wind.

Resumé

Energiøer bliver ofte omtalt som en vigtig komponent i den grønne omstilling i Norden og Baltikum samt i Vest- og Centraleuropa. Konceptet beskriver opførelsen af knudepunkter for elproduktion og konvertering langt ude på havet, hvor vindenergipotentialet er højt. Der findes allerede en række initiativer på området, herunder North Sea Wind Power Hub (2021), og Folketinget har ligeledes besluttet at opføre to energiøer fra 2030 (se Energistyrelsen, 2021). Tanken er at skabe et centralt beliggende kunstigt knudepunkt i europæisk farvand i områder med høj produktion af vedvarende energi – herunder primært havvind. Energiøer er et nyt koncept, og der findes endnu ikke tilstrækkelig ekspertise og viden på området. Optimalt design, teknologimix, tilkoblingen til eksisterende netværk, regulering, markedsdesign og forretningsmodeller er endnu ikke klart definerede, men er retningsgivende for udvikling og profitabilitet. Afhandlingen indeholder tre artikler, der har til formål at belyse følgende to hovedforskningsspørgsmål: (1) Hvad er de vigtigste teknologiske, miljømæssige, økonomiske og samfundsmæssige drivkræfter og udfordringer for udviklingen af energiøer, og hvordan påvirker energiøer elektrolyse på havet? (2) Hvordan påvirker systemkonfiguration og markedsdesign værdien af elektrolyse på energiøer?

I den første artikel, *Risks, Strategies, and Benefits of Offshore Energy Hubs*, udvikles en model inspireret af multikriterieanalyse til vurdering af de vigtigste drivkræfter i udviklingen af energiøer. Heri foreslår jeg en definition af energiøer, præsenterer modellen og undersøger ved hjælp af denne offshore energiinfrastruktur i Nordsøen. Jeg identificerer her fem kriterier, der har betydning for projekternes succes: Miljøgevinsten ved et projekt er stærkt forbundet med valg af materialer og design; ændringer i de nuværende antagelser kan vende op og ned på fordele og ulemper og gøre projekterne til dårlige investeringer; koordineret og integreret planlægning er nøglen til at øge projekteffektiviteten; energiinfrastruktur på havet udgør kun den teknologiske løsning på dekarbonisering af energisystemer men der er samtidig behov for at medtænke samfundsmæssige ønsker og behov; endelig er energiøer i øjeblikket enkeltstående løsninger uden nogen konkurrent, hvilket gør deres fordele usikre på grund af manglende sammenligningsgrundlag.

I den anden artikel, *How to Connect Energy Islands?*, undersøger vi forskellen på at integrere energiøer via enten elsystemet eller brintinfrastruktur. Vi udvikler en kombineret kapacitetsudvidelses- og elmarkedsmodel for at vurdere elektrolysens og elkablernes rolle, når der er høj tilgængelighed af vedvarende energi fra energiøerne. Vi finder, at elsystemet profiterer af sammenkoblingen mellem energiøer og havvindmølleparker. I en scenarieanalyse spiller elektrolyse på øerne en mindre rolle, når det samtidig tillades at bygge brintproduktion på land. Energisystemets infrastruktur til havs konvergerer hen imod et elnet i havet og energiøer med stor elektrolysekapacitet. Vi konstaterer, at der er risiko for, at atomkraft og biomasse bliver brugt som brændsel til elektrolyse frem for havvind. Desuden er kapacitetsudvidelserne i elektrolysekapacitet meget følsomme over for brintprisen, men mindre over for ændringer i kulstofpriserne.

I en opfølgende undersøgelse, *Electrolysis as a Flexibility Resource on Energy Islands*, diskuterer vi elektrolysens operationelle rolle på en energiø. For energiøerne, der i øjeblikket overvejes i Nord- og Østersøen, vurderer vi brintproduktionens potentielle fleksibilitetsydelse og analyserer derefter forskellige markedsintegrationsstrategier. Vi tilpasser markedsintegrationen af energiøerne til den aktuelle debat og sammenligner en enkelt hav-budzone med en situation, hvor energiøen er integreret i en hjemmemarkedszone. Elproduktion fra havvindmøller er forbundet med usikkerhed, og fleksibilitetsressourcer skal kompensere herfor ved at sælge eller købe yderligere elektricitet i de respektive markedssekvenser, dvs. intraday- og systemydelsesmarked. Med artiklen bidrager vi til debatten om hvordan elektrolyse kan udgøre en fleksibel ressource, samt hvordan kombinationen af fluktuerende vindenergi og elektrolyse kan integreres i systemet og markedet. Vi udvikler en to-trins stokastisk optimeringsmodel for at finde den omkostningseffektive markedsløsning til et integreret day-ahead og systemydelsesmarked. Vi finder, at elektrolyse på energiøer vil køre med lave kapacitetsfaktorer og give fleksibilitet i 25–30% af deres driftstid. Derudover er det profitabelt at købe elektricitet til lidt højere gennemsnitlige omkostninger i en hav-budzone, så elektrolyse køres med højere kapacitetsfaktorer sammenlignet med hjemmezonemarkedet. Vi konkluderer, at politik på området bør tage hensyn til værdien af fleksibilitetsressourcerne på havet og mulige mekanismer til at give økonomisk støtte.

Undersøgelsen i de tre artikler fører til følgende konklusion på de overordnede forskningsspørgsmål: Energiøer vil sandsynligvis udvikle sig inden for eller som en del af et havnet og kan levere et miljø for konkurrencedygtig brintproduktion. Øernes specifikke design er endnu ikke defineret, men de første resultater peger i retning af, at energiøer kommer til at danne grobund for flere teknologier inden for energiproduktion, -lagring, og -konvertering. Især den fjerne beliggenhed gør energiøer attraktive for en brintproduktion i stor skala, hvilket i vores analyser også viser sig at være hovedformålet, da de nuværende teknologiomkostninger endnu ikke er konkurrencedygtige med hensyn til fleksibilitetsydelser. Budzonekonfigurationer og skarpe økonomiske rammer for sektorkobling som fremtidskoncept kan være afgørende for, at et projekt kan levere forbedringer til energisystemtransformationen.

Nøgleord: energiøer, energisystemmodellering, elektrolyse, brint, fleksibilitet til bæredygtige energisystemer, budzoner, havanlæg, vindenergi

Contents

Acronyms

CO_2 carbon dioxide

DEI Danish Energy Island

ENTSO-E European Network for Transmission System Operators for Electricity

ESI energy system integration

EU European Union

GHG greenhouse gas

GW gigawatt

GWh gigawatt hour

HBZ home bidding zone

IO industrial organisation

LP linear program

MCA multi-criteria assessment

MW megawatt

MWh megawatt hour

NSWPH North Sea Wind Power Hub

NTC net-transfer capacity

OBZ offshore bidding zone

OEH offshore energy hub

OR operations research

PtG power-to-gas

PV solar photovoltaics

RES renewable energy sources

SP stochastic program

TSO transmission system operator

TYNDP ten-year network development plan

VOM variable operations and maintenance

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Part I

Thesis Context and Summary

CHAPTER 1

Introduction

The past three years of my professional life were dedicated to researching the future and value of offshore energy hubs. The work, conclusions, prospects, and doubts are merged in this thesis. With the help of three connected but independent studies, papers A to C, I was able to work towards answering two overarching research questions that guided the smaller projects. The following chapters of Part I guide the reader from a personal motivation to insights into the research questions and conclude with key findings and a list of exciting future work.

1.1 Motivation

Personal. Growing up close to the sea and in an area with low population density, solar photovoltaics (PV) and wind turbines were an early sight for me. The familiarity came hand in hand with fascination and the feeling that these enriched nature and added beauty to the landscape. Besides the feeling of having so urgently needed renewable energy sources (RES) always close by, I often felt that this was not enough: in many places, countries, and regions humans are threatened by the consequences of climate change, suffering from drought, fires, floods, disappearing sources of food, and more. I developed some frustration because I felt that since the early 1980s, researchers had been highlighting how increased greenhouse gas (GHG) emissions due to human activity threatened the climate and the natural biosphere of our home. I needed to learn more about the science and the reasons for delays in implementing solutions. Through my enthusiasm for mathematics,[1] I first discovered energy system models at TU Berlin in the course EW-MOD (Electricity Market Modelling), and this seemed to be a great link between my curiosity about climate change mitigation, my fascination with renewable energy technol-

[1]To cite my 12-year-old self at home, ”Mom, I love numbers!”.

ogy, and my interest in maths. Great supervision and support and many touch-points with experienced researchers and academic life when I was writing my master's thesis at the Norwegian University of Science and Technology, on local electricity markets, paved the way for the first steps of my academic career. Starting my Ph.D. in 2019, I wanted to see if I could contribute to the discussions about energy system transformation and support society and businesses with knowledge. Moving to Denmark for this project made me curious and excited about large-scale energy systems, and I chose to work on offshore energy systems. On the side, I continued research activities on decentralised energy solutions. After three exciting, challenging, and productive years, I am ready to submit three of my six papers as a Ph.D. thesis—what a journey!

Professional. Commitments and agreements to mitigate climate change and the idea of reducing natural resource dependence have led to the need for new technical, economic, and societal solutions. The field of engineering researches and develops technology using renewable sources such as wind, sun, and water, and it constantly progresses to improve existing solutions. Economics works on improving boundary conditions to enable an efficient, affordable transition while society, with the help of representatives, is in the process of navigating and deciding on strategies and changes to handle the crisis. Solutions for renewable offshore technology and energy system integration are in the making and will be in demand. With the interdisciplinary research I have done over the past three years, I aim to contribute to the academic discussion and to inform political debates on energy system transformation, providing a service to society.

1.2 Context and Challenges

This thesis developed in the context of energy system transformation to support climate change mitigation and reduce the use of natural resources for energy purposes. There are two levels to the work: a very broad placement in the big field of sustainability research in the context of decarbonising the economy, and a narrow placement into the field of research on offshore energy systems development, specifically tailored to the needs of Europe.

Broader Scope. The decarbonisation of the energy system has been an action item in many countries for many years, not only because of the Paris Climate Agreement,[2] in which 196 parties agreed to limit global warming to well below 2°C, but also because every year the weather becomes more extreme and the impact is directly noticeable in more and more regions of the world.[3] In recent summers (including 2022), wildfires reached and burned larger areas each year, underlining that climate change is real and present. The energy sector is a large contributor (usually the largest) to GHG emissions, which have been identified as the main accelerators and causes of global warming (San-Miguel-Ayanz et al., 2021). As a consequence, and in a world so dependent on energy and electricity, this sector needs to undergo a transformation to reduce GHG emissions. One part of the current approach to reducing emissions in the energy sector is the large-scale deployment of RES in connection with rethinking the system infrastructure and energy business models. RES have not only emerged as a means to climate change mitigation, they also present option for avoiding the fuel crises that develop alongside geopolitical conflicts, with the war in Ukraine being the most recent example, and are the cheapest option.

Narrow Scope. Within the large energy system and its restructuring in Europe, the idea of an offshore energy hub (OEH) has been presented as part of the solution. OEHs—which are also called *energy islands*, and I use the terms as synonyms—are seen as a point of collection for electricity generated from offshore winds in their close vicinity and may interconnect several energy markets and countries (see *Paper A*). Due to the *offshore* nature of the concept, investments and project management for OEHs are at first relevant to countries with sea access. While offshore energy technology is experiencing a boost, the European Union (EU) has big plans for the sea to be of high value, not just for a net-zero emission energy system, but also a future hydrogen economy (European Commission & THEMA Consulting group, 2020). Denmark has political plans for OEHs. A European consortium presented a specific project, and other actors, for example Germany and Norway, are developing similar ideas for their

[2]Paris Agreement from December 12, 2015. FCCC/CP/2015/10/Add.1: www.unfcc.int.

[3]This, of course, does not justify delays to avoid damages to all areas of the world, but it is part of the sad truth.

areas in the North and Baltic Seas. One driver of these projects is the idea of exploiting large wind resources and benefiting from prospects of sector coupling at the same time (see *Paper B*). Winds are strong and more consistent offshore (Esteban et al., 2011), and sector coupling can be a way to efficiently decarbonise the transport and heat sectors with RES (Münster et al., 2020). The projects are also driven by increasing opposition to onshore infrastructure projects, such as grid expansion, onshore wind, and new industrial facilities. A first step at sea would be the connection of offshore wind using electrolysers (see *Paper C*) to increase RES-based electricity generation and the production of green hydrogen.[4]

Challenges The large-scale exploitation of offshore wind resources is a new element in the plans for the RES roll-out. The EU's strategy for offshore wind is a starting point to harness wind resources in Europe at sea. But the more innovative the design, the more difficult the implementation: regulatory frameworks, market designs, and business models must be updated to push energy efficiency gains to the limits when setting up offshore infrastructure. The academic literature currently has only a few studies contributing to the discussion of OEHs. In particular, the subject of sector coupling offshore and on such OEHs is largely untouched in the literature, but research is needed to independently inform policymakers and offer new approaches. In discussions of sector coupling in this specific offshore context, most ideas target the combination of offshore wind technology with electrolysis to meet expected hydrogen demand with renewable electricity-based hydrogen, but this setup is, to a large extent, both technically and economically unexplored. Due to the novelty, the implementation of sector coupling offshore calls for a new stream of literature to define roles and structures for integrated systems in an offshore setting with no conventional energy demand. Further, market design and integration into the electricity and potentially gas markets must be done efficiently and could require rethinking the current setup. The envisioned interconnection through offshore wind parks is also unexplored territory, both technically and economically: the consequences for prices, trade, and welfare are unknown, and guidance is of high importance to avoid failures,

[4] Hydrogen is a colourless gas. "Green" refers to the ecologically clean origin of the electricity used in electrolysis to split water into hydrogen and oxygen.

distributional effects, and technical problems.

1.3 Scientific Contributions

With the above-mentioned challenges in mind, and under the assumption that early sector coupling concepts offshore will connect wind energy with electrolysers, I posed two guiding research questions for this thesis:

1. What are the main technological, environmental, economic, and societal drivers of and challenges for the development of offshore energy hubs, and what is their impact on offshore electrolysis?
2. How do system configuration and market design influence the value of electrolysis on offshore energy hubs?

Together with my co-authors, I worked on three sub-projects to develop the knowledge needed to answer these questions. Each sub-project developed into a scientific article with a different strength and contribution. The solo-authored *Paper A* provides the foundational overview of the topic and analyses the value and risk of OEH projects. The analysis uses multi-criteria assessment (MCA) to structure and evaluate the literature on offshore energy, and the results help answer the first research question. I identify technological, economic, ecological, and societal risks and prospects of the projects and conclude by summarising a set of important trade-offs to be considered. The next two projects take up some of the identified challenges and apply quantitative and data-driven methods to find answers. In *Paper B*, Paul E. Seifert, Ruud Egging-Bratseth, Jens Weibezahn, and I develop a capacity expansion model to identify the trade-offs between connecting OEHs via hydrogen, via electricity infrastructure, and via a combination of the two. The insights from this study feed into the discussion of offshore system configuration and potential drivers for coupling hydrogen and electricity at sea, and thus they provide knowledge for both research questions. In *Paper C*, together with Yannick Werner, Ruud Egging-Bratseth, and Jalal Kazempour, I develop a market model that includes uncertainty about renewable energy production to assess the value of electrolysers for flexibility provision. From our analysis, we learned about the interplay of renewable energy production, bidding zone configuration, market prices and hydrogen quantities produced, which I use to support findings in *Paper A* and *Paper B*.

The overall outcome of the thesis is three contributions. First, the articles all include policy guidance, and the last paper specifically formulates four policy recommendations. Second, *Paper B* and *Paper C* extend existing methodological frameworks to hydrogen and electricity market integration. And third, this work suggests new system design and bidding zone configurations for offshore energy systems. We find that there are no comparative projects so far, and therefore we explore how the system can evolve and what the implications could be for the offshore electrolyser in one possible design. In our results, we find that a system with OEHs would develop into a setup combining a meshed offshore grid connecting close-to-shore wind parks and countries with a hydrogen hub far out at sea. The role of this hydrogen hub would then mainly be the production of gas from available wind energy and the supply of a fair share of electricity via cables to shore.

1.4 Outline of the Thesis

This thesis has two parts. Part I is organised into four chapters and presents the framework of the thesis. Part II is a collection of my research articles. In the first part, I give a comprehensive presentation of the overall work, including a short summary of the second part. Chapter 1 motivates and introduces the topic, provides context, lists contributions, and gives structural information. Chapter 2 deepens the context presented in Section 1.2, including a thematic background in Section 2.1 and a methodological background in Section 2.2. Chapter 3 gives answers to the research questions, links these answers to the individual papers, and finally discusses the contributions and insights we gained for the implementation of OEHs. Chapter 4 summarises the findings, concludes the three years of research on OEHs and points to research ideas and needs for further development and progress. It follows Part II with the collection of my papers.

1.5 List of Papers and Publications

The papers that form the core of this thesis are listed below and referred to as Papers A to C. The following table gives the title, author information, and author contributions for each. The papers are included in Part II of the thesis as Chapters A to C.

Paper A:	**Risks, Strategies, and Benefits of Offshore Energy Hubs** A Literature-Based Survey
	Single-author original research article.
Paper B:	**How to Connect Energy Islands?** Trade-Offs between Hydrogen and Electricity Infrastructure
	Co-authored by Alexandra Lüth, Paul Seifert, Ruud Egging-Bratseth, and Jens Weibezahn.
	AL: conceptualisation, data curation, visualisation, writing - original draft, writing - review & editing. PS: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. REB: conceptualisation, supervision, writing - review & editing. JW: conceptualisation, supervision, writing - review & editing.
Paper C:	**Electrolysis as a Flexibility Resource on Energy Islands** The Case of the North Sea
	Co-authored by Alexandra Lüth, Yannick Werner, Ruud Egging-Bratseth, and Jalal Kazempour. The article is submitted to *Energy Policy*.
	AL: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. YW: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. REB: conceptualisation, supervision, writing - review & editing. JK: conceptualisation, supervision, writing - review & editing.

In addition to the articles included here to answer the research questions, I worked on three other papers during my Ph.D. studies. The list below presents these already published articles, which focus on decentralised energy systems and local electricity markets including a digression on electrification in the global south. Due to the different topics of papers D to F, they are not included in the core of this thesis. However, they are listed and provide contributions to the discussion of the value of small-scale renewable energy resources and systems. I provide the bibliographic information and a reference to my contribution.

Paper D: **On Distributional Effects in Local Electricity Market Designs:**
Evidence from a German Case Study

Lüth, A., Weibezahn, J., & Zepter, J. M. (2020). On Distributional Effects in Local Electricity Market Designs: Evidence from a German Case Study. *Energies, 13*(8), [1993]. doi:10.3390/en13081993

AL: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. JW: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. JMZ: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing.

Paper E: **Crowd Balancing:**
A Model for Future Grids

Lüth, A., & Jamasb, T. (2020). Crowd Balancing: A Model for Future Grids. *Oxford Energy Forum*, (124), 31-34. www.oxfordenergy.org/wpcms/wp-content/uploads/2020/09/OEF124.pdf

AL: conceptualisation, visualisation, writing - original draft, writing - review & editing. TJ: conceptualisation, writing - review & editing.

Paper F: **Prosumer Empowerment through Community Power Purchase Agreements:**
A Market Design for Swarm Grids

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AL: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. RD: conceptualisation, investigation, validation, writing - original draft, writing - review & editing. JW: conceptualisation, data curation, software, visualisation, writing - original draft, writing - review & editing. SG: conceptualisation, resources, writing - review & editing.

CHAPTER 2

Background

Pathways to completing the energy system transformation to a low-emission sector have been important and sensitive topics in recent years in research, as well as in politics and society. There is broad, fundamental evidence of the need for change, resulting in the emergence of various very specific fields of research surrounding the energy system transformation. This thesis focuses on a part of the role of offshore systems in the future energy system and applies techno-economic analysis in the form of operations research–based energy system models. The following parts provide the context in which this work emerged, in Section 2.1, and then the fundamentals of the methods used to conduct the analyses, in Section 2.2.

2.1 Topics and Thematic Introduction

Within the large field of research on climate change, decarbonisation of the economy, and a sustainable future, this work contributes to the discussions of energy system transformation by way of increasing electricity generation from RES, specifically from offshore wind. I discuss the use of large offshore wind hubs in connection with energy conversion at sea in the context of offshore energy hubs. The following sections provide a thematic background, starting with a description of the development of RES in the energy system in Section 2.1.1. In Section 2.1.2, I describe the role of offshore wind, and I complete the thematic background in Section 2.1.3 by introducing the concept of OEHs in detail.

2.1.1 Renewable Energy Sources, Energy Systems, and Sector Integration

From the late 1990s onward, there has been a consensus among a broad range of researchers advocating for a transition to clean (low GHG emission) energy production, entailing a shift from fossil fuels to low carbon emission fuels. This has been backed by evidence that GHG emissions accelerate climate change, and that society must ban those to prevent drastic changes to the climate (IPCC, 2013). In the EU, the energy sector contributed 1.14 billion tonnes of carbon dioxide emissions in 1990 (30% of total emissions; EEA, 2002), and the sector still produced 780 million tonnes (25.8% of total emissions) in 2020 (Eurostat, 2019).

In a parallel debate, the geopolitics of natural resources and resource independence gained momentum. Penetration of RES shifted the rules and relationships of established fossil fuel trading partners (Scholten et al., 2020). In 2022, due to the war in Ukraine, this topic has been peaking in relevance, and the reduction of energy dependency is becoming a timely issue, for example for Germany. RES are part of the solution and an equally important driver of system transformation, because they have been shown to support international security and peace (Vakulchuk et al., 2020). The energy system transformation has, at the time of this writing, not yet made the desired progress, neither to increase natural resource independence nor to get significantly closer to mitigating climate change.

The era of RES started with the first PV panels in the early twentieth century (Perlin, 1999). Wind energy as we know it today made its first strong developments in parallel to the oil crisis (Kaldellis & Zafirakis, 2011), and its offshore counterpart started large-scale deployment in 1991 (Bilgili et al., 2011). These technologies were initially seen as a way towards a sector without exhaustible fossil fuels, based entirely on clean energy sources. Further and still ongoing progress can be observed in a series of indicators: cost developments and the emergence of new concepts, system designs, and paradigms. Renewable energy technology has become significantly cheaper: the cost of solar technology, for example, dropped by approximately 80% between 2010 and 2020, down to USD 883/kW (IRENA, 2021). Figure 2.1 shows the cost developments of wind energy and PV. With this background, the electricity mix changed in recent years to a system with more RES (von Hirschhausen et al., 2018, ch. 10). The decreasing prices led to cost-competitive technology and paved the way for new and more affordable RES concepts, such as OEHs.

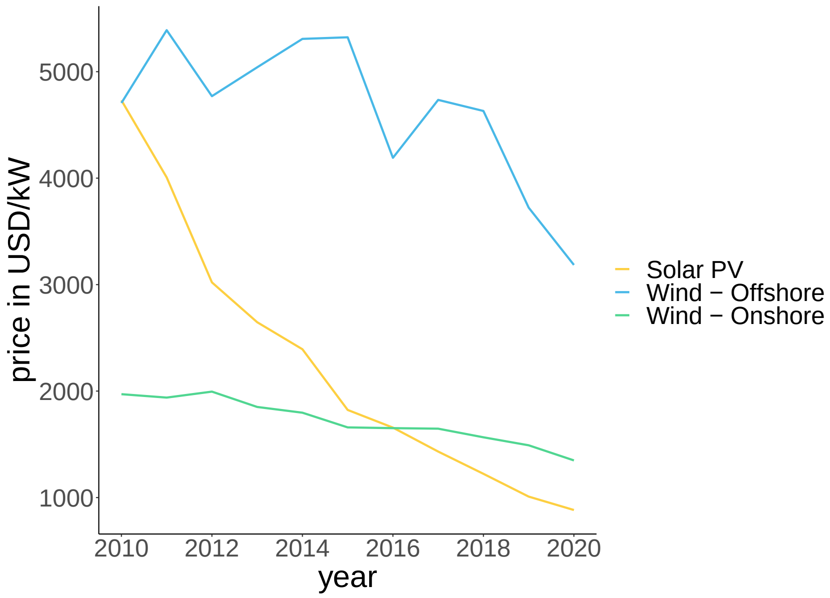


Figure 2.1. Cost development of renewable energy technology.
Data source: IRENA (2021).

Hand in hand with the new technology, different energy system setups developed, and new community concepts, virtual power plants, and local markets with aggregators resulted from changes in the size and location of energy production. Due to the characteristics of renewable energy technologies, such as wind, PV, and hydropower, the system architecture and design were forced to change. Large, centralised power plants (e.g., coal, gas, and nuclear based) at gigawatt sizes per unit were replaced with smaller renewables at the megawatt size per unit. Their placement no longer depended on the location of the load centre but on areas with high wind or solar potential—often rural areas at large distances from the nearest urban or industrial demand hub. Further, certainty in production was taken away, and dependence on wind and sun became a new determinant in the system, introducing uncertainty in production. Uncertainty had not been a component at the production level before, and only fuel prices would fluctuate. RES, however, are cheap in marginal production costs and introduce new economics to the market.

A RES-based system also implies that future energy systems will be electricity-based, and electricity is not as easily storable as oil, gas, or coal. Besides electricity storage, this leads to the need to exploit technical synergies to increase energy efficiency. Energy system integration (ESI) is a particularly relevant concept for this. In the process of energy system transformation, ESI emerged as an efficient[5] approach to large-scale electrification and reduction of GHG emissions in the industry, transport, and heat sectors. ESI[6] is defined as a form of integrated operation and planning of various energy domains and traditionally separated industries, for example by joining electricity, heat, gas and mobility, and there are several levels to it: technical, institutional, and economic (Ramsebner et al., 2021; Silvast et al., 2021). ESI enables better and more efficient electrification of sectors that still depend largely on fossil fuels, for example heating and transport (Münster et al., 2020); linking these sectors allows for the exploitation of synergies and resource-efficient use of available electricity.

In *Paper B* and *Paper C*, we work with the concept of ESI and investigate its offshore potential in large wind power hubs combined with electrolysis (gas production): an integration of the electricity and gas sectors along with transport based on electricity or renewable gas or other fuels. We assume that the benefits and prospects of ESI will materialise in the range of what is shown in studies, and we take this further by investigating its potential at sea, which so far has only been touched on by Gea Bermúdez et al. (2021) and Zhang et al. (2022); we focus on infrastructure development in *Paper B* and market design in *Paper C*.

2.1.2 Offshore Energy Systems

In the process of transforming energy systems, production technology shifted, and the new technology has different needs: strong winds, many sunny hours, or mountains with large water reserves. Wind energy is especially important for decarbonization, and at sea the winds blow at a higher intensity and more stable levels. This invites us to move production hubs far out to the sea and opens a new era of energy production offshore. Offshore wind technology started in 1991 in Denmark, where the first commercial offshore wind park was commissioned in the Baltic Sea (Bilgili

[5]Possibly also the only solution to decarbonise industry, transport, and heating.

[6]Energy system integration is often called sector integration or sector coupling, with no defined difference between the concepts.

et al., 2011). The technology has undergone major development since, and by 2018 23 GW were deployed worldwide, with 17 GW added between 2010 and 2018 in the EU (IEA, 2019). In 2020, the European Commission specified plans and ambitions for offshore wind in a strategy (European Commission & THEMA Consulting group, 2020).

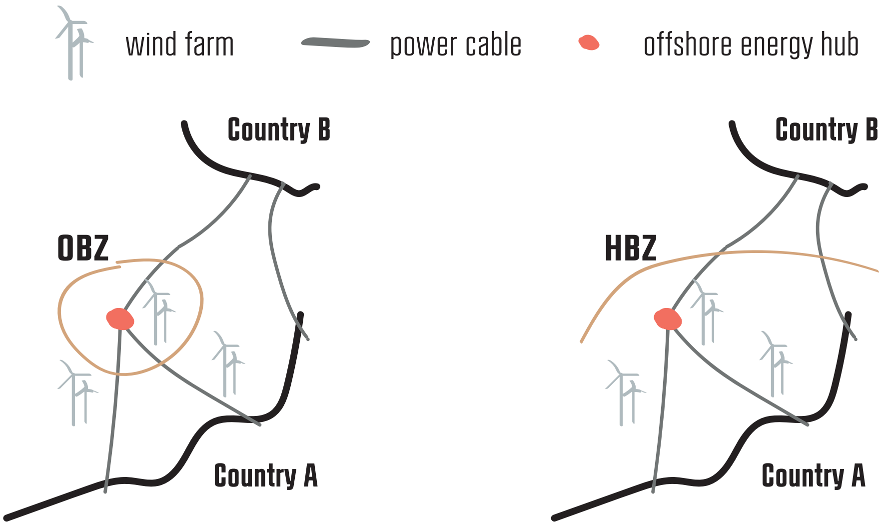
Another major driver of offshore installations is the growing opposition to onshore energy infrastructures, which includes NIMBY (not-in-my-backyard) activism and protests against new infrastructure in rural areas due to intrusion, land use, and loss of scenic views and biodiversity. As shown in *Paper A*, offshore energy infrastructure faces similar biodiversity and land-use problems, but public acceptance is higher, so resistance and citizen opposition do not delay the process. An important bottleneck in some countries, for both onshore and offshore processes, is the bureaucracy around investment and project approval and the lack of policy certainty (many examples in Germany can be found, but Denmark is also facing new movements and acceptance problems; see Hevia-Koch and Klinge Jacobsen (2019)). *Paper B* and *Paper C* assume that offshore wind expansion plans in Europe will go as planned and desired. This implies that the suppositions of a large body of research literature are taken for granted, including successful offshore wind support policies, materialisation of enhanced offshore interconnection, and adjusted regulatory frameworks for offshore systems.

Offshore Wind Policy. The liberalised electricity market requires the operators of wind farms to compete in the market. In their first years, investment in and operation of wind farms was not profitable and needed support policies. Poudineh et al. (2017, ch. 4) distinguished two general approaches: direct and indirect policies. Direct support policies can either be paid on production, for example with a feed-in tariff when a producer feeds into the grid, or as a support for investment, with a fixed amount per unit built. Indirect policies take the form of economy-wide goals and mechanisms that, for example, make it attractive to emit less GHG because the cost of emissions has been increased by carbon taxes or the need to buy emission rights. Theoretically, indirect support polices are economically more efficient, but Green and Vasilakos (2011) show using historical examples that tender policies and feed-in-premiums in Denmark were the most efficient up to that time.

Today, offshore wind technology has reached a market-competitive level (Jansen et al., 2020). With competitive technology and offshore potential, discussions have evolved around whether different market conditions or changes in zone boundaries could enhance development. In a sandbox case, the offshore wind farm Kriegers Flak was commissioned. This wind farm connects to two countries, Germany and Denmark, and is a novel combined solution of RES connection and interconnection (Marten et al., 2018). The attempt to rethink traditional wind farm-owner-country connections by reforming offshore bidding zones is also discussed in a TSO-perspective paper by Energinet et al. (2020) and is picked up here in *Paper C*, where we discuss the role of offshore bidding zones. Our approach follows the structure described by the Nordic TSOs, Weichenhain et al. (2019) and Kitzing and Garzón González (2020).

The bidding zone discussion has evolved around the question whether offshore wind hubs at large scales should constitute a separate zone or be integrated in their home markets, as shown in Figure 2.2. In the offshore bidding zone (OBZ) configuration, the wind farm constitutes its own bidding zone, and exchanges with connected markets take into account network constraints. In the home bidding zone (HBZ) configuration, the wind farm participates in the market of the land's owner, and thus network constraints between hub and shore are neglected. The discussion of the two concepts has been built around literature on pricing in electricity markets. Zonal and nodal pricing are the most common concepts. Markets with nodal pricing are often seen as the economically efficient benchmark for electricity markets (Brunekreeft et al., 2005; Holmberg & Lazarczyk, 2015), yet existing markets with zonal structures are not developing towards nodal pricing. In line with the debate about redefining market zones in Europe (ACER, 2022) to more efficiently incentivise investment and reduce congestion management costs, the topic is also relevant for future offshore energy systems.

There is no consensus yet on how to integrate and connect large offshore wind power hubs into the markets. The decision about market integration, however, will need to be made hand in hand with decisions about technical system design. Research and industry have been discussing several approaches that also veer widely from standard approaches. The main ideas are described below.



(a) OBZ configuration. **(b)** HBZ configuration.

Figure 2.2. Two different bidding zone configurations for offshore wind power hubs. In an OBZ, a hub constitutes its own bidding zone, while in an HBZ the hub participates in Country A.
Source: Author's illustration.

Integration of Offshore RES. The integration of offshore wind technology into the electricity system has been under development for a while. The onshore network expansion needed to deliver electricity from the coast to customers in urban areas became particularly difficult early on. But regulatory frameworks also needed to be updated, and markets had to react to low-cost electricity production with high uncertainty. Technically, offshore wind farms at large gigawatt sizes are most efficiently connected to shore by high-voltage direct current lines, as is also the case for onshore electricity infrastructure over large distances (Flourentzou et al., 2009). Considering the large area and high RES potential at sea, research on grid topology for connecting potential wind power hubs, especially in the North Sea, soon converged on the idea of a meshed offshore grid (Chen, 2018; Trötscher & Korpås, 2011). This grid would connect countries via offshore wind farms. In techno-economic analyses, Cole et al. (2015) and Egerer et al. (2013) identify positive impacts of offshore grids on the welfare of countries that could connect to them. These effects differ among studies (Gorenstein Dedecca & Hakvoort, 2016), however, and the final design and coordinated development will influence the impact significantly (Dedecca et al., 2019). Besides pure technical characteristics and the role of joint planning, the economic framework in a setting with many cross-border connections will affect and drive developments. Currently, conventional markets with demand and supply connect through cross-border lines. An offshore grid would be an electricity network connecting countries and markets via production hubs without conventional demand: an unexplored concept, and one without suitable regulation and operational guidelines. Research on governance and regulation calls for an innovative solution and suggests implementing a supra-national operator (Sunila et al., 2019) subject to more regional economic network regulation (Meeus, 2015). Any progress in the development of offshore wind regulation and market integration will affect sector coupling offshore as well. When we deploy more offshore technology, we gain experience and move along a learning curve. The OEH concept explored in this thesis assumes that the background above is a solid enough groundwork for the hubs to materialise.

2.1.3 Offshore Energy Hubs

From offshore wind, interconnection, and offshore grids all the way to OEHs, the vision of OEHs includes a range of energy technology, generation, conversion, and storage, all of them placed offshore. The term *offshore energy hub* is derived from the idea of energy hubs moved to an offshore context. The term *energy islands* is often used for the same idea. In this thesis, *offshore energy hub* is the dominant term, but I treat the terms as interchangeable. All the papers in this thesis discuss different aspects of offshore energy hubs. *Paper A* suggests a definition of the concept and contributes to a research framework for OEHs. To make the background of the papers comprehensive and complete, the following paragraphs rephrase the findings of *Paper A*.

OEH projects are envisioned as bringing advantages such as improved efficiency, transmission operations, flexibility, and price, similar to onshore energy hubs (Geidl et al., 2007). The idea emerged in the context of offshore wind expansions, and the first specific project proposal was made by the *North Sea Wind Power Hub* consortium in 2016.[7] The Danish government announced in 2020 that it would support and require the

[7]See North Sea Wind Power Hub: www.northseawindpowerhub.eu.

development of two equivalent projects in the Danish waters of the North and Baltic Seas. Industry stakeholders are now in the process of developing concepts, and researchers are contributing articles to the discussion. On the basis of the current literature on OEHs and related topics, I develop the following definition of offshore energy hubs in *Paper A*:

> *An offshore energy hub is a fully renewable energy resource-based combination of assets that link at least two services, such as electricity generation, interconnection, and offshore storage. These services are relevant to energy system development and operation and foster decarbonisation of the energy sector while preserving the environment.*

Figure 2.3 visualises this definition and shows one version how an OEH could look: interconnecting several countries through a hub in a centre of offshore wind generation, the OEH gathers technology to store, convert, and condition energy.

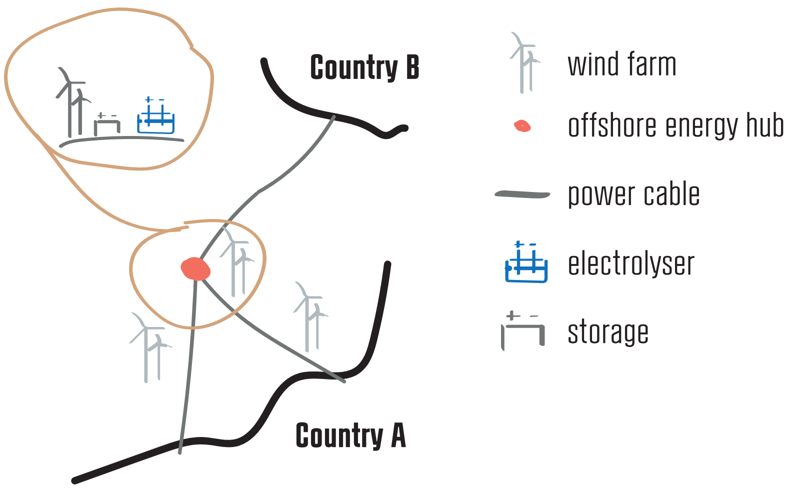


Figure 2.3. An abstract sketch of an OEH following first visions.
Source: Author's illustration.

2.2 Methodologies

All the analyses in this thesis combine multiple fields and methods, leading to an interdisciplinary thesis with most of its theoretical content in economics and some in operations research. Due to the technical nature of the energy sector, techno-economic analysis provides prominent advantages in assessing, for example, policies and market design. The following sections present the theoretical fundamentals relevant to this work. Section 2.2.1 (energy economics), Section 2.2.2 (operations research), and Section 2.2.3 (energy system modelling) present the fields independently first, and a description of the relevance of combining them for this work is given in Section 2.2.4.

2.2.1 Energy Economics

Energy economics gives a framework for the topics dealt with in this thesis and either provides the tools to analyse the research questions or is at the core of the analysis. To clarify the role of energy economics in this thesis, the following paragraphs describe the leading concepts that *Paper B* and *Paper C* in particular are based on. I further highlight the relevant key areas that were decisive in developing *Paper A*.

The economics of the energy industry follows a set of standard concepts that have their origin in classical and neoclassical economics. Many analyses in energy economics focus on electricity or energy markets and use microeconomics. In situations of taxation and high-level policymaking, macroeconomics leads (Harris, 2006). As in other industries, the energy industry is characterised as having producers and consumers, which means there are demand, supply, and costs as in classical economic models. Energy markets are viewed with the underlying idea that the markets determine the price through rational, optimising agents with stated preference functions aiming to achieve an equilibrium outcome. According to Bhattacharyya (2019), energy economics is concerned with the following points:

1. *The economics of energy supply involving exploration, development, production, transportation, storage, transformation and delivery of energy commodities;*
2. *The economic logic of energy consumption decisions by various users;*

3. *Energy transactions through alternative market arrangements and their governance;*
4. *The economic dimension of social and environmental impacts of energy use; and*
5. *The planning, policy and performance of the industries, actors and governance mechanisms.*

taken from Bhattacharyya (2019, p. 2)

To analyse the above concerns, energy economists apply concepts originating in various economic fields, such as industrial organisation, behavioural economics, environmental and resource economics, econometrics, and business economics, to name a few. Together with game theory applied to economics, insights and methods of these fields serve applied energy economists as a toolbox. To highlight the dominant part of the theory for this thesis, I summarise the role of industrial organisation and the specifics of market design below.

Industrial organisation (IO) deals with the functioning of markets and industries. Its research is often focused on competition and the role of market power (Cabral, 2017). Concepts of industrial organisation are of high relevance to the energy industry and energy economists draw frequently from the insights. IO is concerned with consumers, firms, markets, prices, and market power. Electricity markets combine several firms that compete on multiple markets offering different products in a repeated manner. Kellogg and Reguant (2021) provide an extensive overview of the contributions of IO to understanding energy markets and sector regulation. Deregulated markets that evolved from a monopolistic structure are now in the process of immense restructuring and development to accommodate renewable energy resources. The authors highlight that IO can contribute to developing an efficient sector by using its theory for designing energy markets, investigating the role of emerging industries, such as the of electric vehicles, and the future of conventional energy technologies. For *Paper B* and *Paper C*, we neglect market power as such, but are concerned with a functioning, competitive market and evaluate the impact of different designs by suggesting two bidding zone configurations for OEHs.

The decision on the configuration of the bidding zones is part of what is often called market design. This practice is said to have evolved from mechanism design and game theory and is now a substantial part of the development of various marketplaces (Roth & Wilson, 2019). With changing patterns and characteristics in the energy systems, the framework for electricity and energy markets changes as well, which invites energy economists to rethink market rules and boundary conditions. Paul Milgrom, who together with Alvin Roth is often referred to as the founder of this practice, defines market design as *"a kind of economic engineering, utilising laboratory research, game theory, algorithms, simulations, and more. Its challenges inspire us to rethink longstanding fundamentals of economic theory."* (Milgrom, 2009).

For large parts of this thesis, I focus on the economics of the energy supply in combination with a stiff, inelastic consumption pattern. For *Paper A*, I use all the listed points to define the guiding criteria for the analysis. In addition, *Paper C* adds a layer of policy recommendations for the performance of market configurations where economics provides a set of tools that policymakers can use to realise the guidance, as in Harris (2006, p. 407). To set up our market model in *Paper B* and *Paper C*, we construct both our production and demand functions by stacking bids side by side, obtaining the merit order. Clearing the market, we adopt all the above assumptions about markets and determine a price without including market power and disregarding the game theoretic and behavioural details. OEHs take energy economics into a new area and this thesis contributes to exploring this highly topical concept.

2.2.2 Operations Research

Besides the foundational economic theory, this thesis makes use of two models from operations research (OR): *Paper B* develops a linear program, and *Paper C* uses stochastic programming.

The field of OR developed quickly during and after World War II as a way to increase efficiency in military exercises (Gass & Fu, 2013). In their summary and elaboration of the history of OR, the authors highlight the period between 1936 and 1946 as the time of its origin. The following years, until 1956, then cover the discipline's expansion and professionalisation with researchers such as George B. Dantzig, Tjalling C. Koopmans, and Leonid V. Kantorovich. Based on the multi-disciplinary background of its founders—mathematicians, physicians, economists—OR has traces in many fields now, too. Applications of OR are aimed at finding the best ways to improve the efficiency of processes and manage organisations (Hillier & Lieberman, 2021). OR researchers focus on developing analytical models and methods to support decision-making. In this thesis, I include two papers with applications of two OR methods to conduct analyses of the energy sector. In the following section, I describe the theoretical foundations of the two applied models. Linear and stochastic programs are a subset of mathematical programs, which include among others integer programs and equilibrium models.

Linear Programming. Among the standard tools of OR is linear programming. In the generic form, we can describe a linear program (LP) in mathematical terms through Equations (2.1)-(2.3) (Vlahos et al., 1995, p. 7). As the name implies, the problem contains a set of linear equations and is convex. The objective (Eq. (2.1)) is to find the values for the decision variables of vector x such that the function is minimised, accounting for the cost parameters c^T. The objective is subject to linear constraints (Eq. (2.2)) limiting the vector x by a matrix A of multipliers to parameters in vector b. All the values in x are non-negative (Eq. (2.3)).

$$\min_{x} \quad c^{\mathrm{T}} x \tag{2.1}$$

$$\text{s.t.} \quad Ax = b \tag{2.2}$$

$$x \geq 0 \tag{2.3}$$

A comprehensive introduction to linear programming can be found in Hillier and Lieberman (2021) and in Dantzig (1963), who also developed the most common solution method for linear programs, the Simplex algorithm.

Stochastic Programming. Further in the thesis, we use a two-stage stochastic program to model uncertainty in renewable energy generation. A stochastic program (SP) extends the LP described above by including uncertainty-related adjustments in a second stage. Equations (2.4)-(2.6) depict the mathematical formulation of such a problem (Birge & Louveaux, 2011, p. 10). The second stage, in which the adjustments are made, is represented by $Q(x, \xi) = \min\{q^{\mathrm{T}}y|Wy = h - Tx, y \geq 0\}$ and the expectation E in dependence of ξ. $Q(x, \xi)$ is the second-stage problem in which y is the vector of adjustment actions with the cost multiplier q^T for this stage. The constraints for this stage are given by the matrix W, restricted by the vector of bounds h and the links to T and the first-stage decision variables in vector x.

$$\min_{x} \quad c^{\mathrm{T}}x + E_{\xi}Q(x, \xi) \tag{2.4}$$

$$\text{s.t.} \quad Ax = b \tag{2.5}$$

$$x \geq 0 \tag{2.6}$$

Introductions to stochastic programming and applications can be found in Birge and Louveaux (2011) and Vlahos et al. (1995). We use a model type for energy system applications described in Morales et al. (2014, p. 64).

Capacity Expansion Model. Capacity expansion models add an investment component to a mathematical program to determine optimal production capacities (Luss, 1982). The capacity extension can be included in an LP or an SP and also in other mathematical programs. In the context of energy or transport applications, for example, the capacity determined in the models can also target network capacity expansions, such as roads, cables, or pipelines (Soroudi, 2017).

2.2.3 Energy System Modelling: Techno-Economic Analysis

> *"All models are wrong, but some are useful."* (George Box, 1976)

Models are seldom correct, and their numbers are not exact results, but they do help us understand. Energy systems are often complex and combine technical and economic characteristics that it is important to keep together. In light of this techno-economic nature, energy system models emerged as an important tool for policy, decision-making, and system design in the 1990s (Conejo & Prieto, 2001).

In general, energy system models use mathematical programs to describe energy systems. Since the late 80s, more and more energy system and market models have emerged (Conejo & Prieto, 2001; Murphy et al., 1988), and the literature on mathematical models for electricity markets, energy markets, and energy systems has grown tremendously. The mathematical programs used include linear and stochastic programs with and without capacity expansion, along with other model types and techniques of OR. Apart from the literature with applications to the energy system, there is an extensive body of academic research just on power system and electricity market modelling.

The many energy models have been developed for various applications and with differing details. Figure 2.4 shows six types of energy models sorted by level of detail and scope. Ringkjøb et al. (2018) review energy system models to provide an overview of existing tools, including a detailed description and evaluation of methods and characteristics. To structure the large number of models into categories, Hall and Buckley (2016) develop a classification scheme for energy system models based on models developed for the United Kingdom. Lopion et al. (2018) compare the scheme of Hall and Buckley to two other sets of criteria and identify 19 characteristics, which can be clustered into the model's purpose, technical information, and mathematical detail (Weibezahn, 2020).

Within the large world of modelling, we can fit the models in this thesis into several categories. The model developed in *Paper B* belongs to the group that has defined systems with restricted regional borders in their scope and touches on a limited number of details. Section 2.2.2 expands on the mathematical framework for this model. General applications tackle questions about the sizing of power plants, networks, and the dimensioning of systems. *Paper C* works with a production model for electricity with higher detail on technologies and power plant characteristics. But this paper also includes some characteristics of energy system models due to the link to hydrogen production. The main decision elements of the model are the operational restrictions, which reflect more technical constraints and reduce system flexibility.

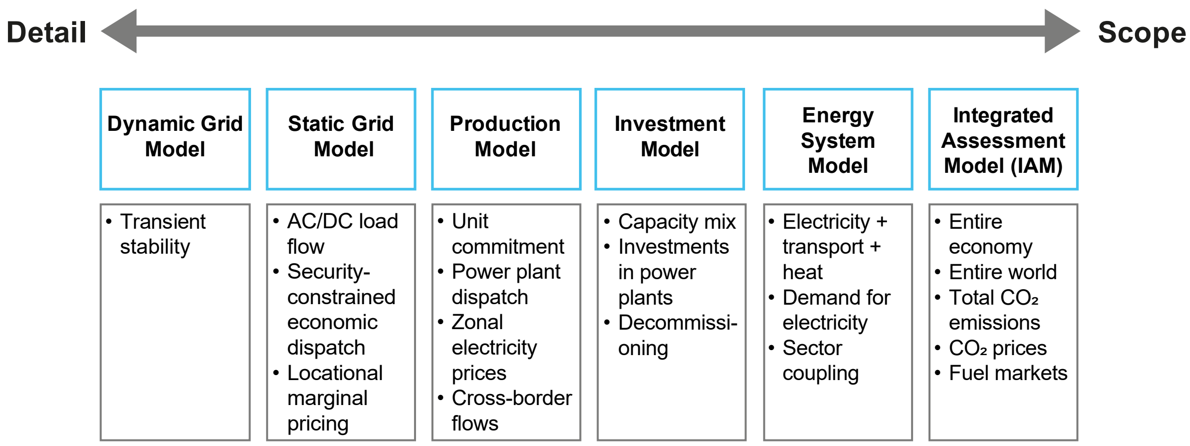


Figure 2.4. Types of of models, characterised by their detail and scope.
Source: Based on illustrations by Lion Hirth and Jens Weibezahn.

2.2.4 An Interdisciplinary Approach

Research in economics can sometimes be enriched by the use of methods of OR that are well-tailored to analysing consumption, production, and allocation issues (Beilby, 1975), and economics, at its roots, tackled questions of allocation. The most common applications of OR in economics deal with game-theoretic problems (Leinfellner et al., 1997), mechanism design (Myerson, 1989; Vohra, 2011), and auctions (Myerson, 1981; Samuelson, 2002). There is a large body of literature on the uses of and perspectives on economic problems in OR. In addition, we find many overlaps in policy analysis, finance, game theory, and decision analysis, and sector-wide questions especially profit from the expertise and methods of OR, for example, to analyse the impact of policies and to support decisions.

Energy has always been a topic in both economics and OR. This specific link originates from a two-fold setting. In the early 1990s, the energy sector went through a heavy restructuring and unbundling process, introducing competition. This was driven foremost by economics, and regulation of the sector is still driven by economic theory. On the other hand, the introduced markets and market clearing align seamlessly with the theory of OR and use linear and integer models to match supply and demand (Murphy, 2013). The authors elaborated that the energy sector has an interesting characteristic: the key for research is to include technology choices in the decision, and this is best done using interdisciplinary research.

This thesis analyses the impacts on the energy system and market when hydrogen and electricity solutions are combined in a location between existing market zones. To identify direction of movement and the outcomes of different system configurations, we apply standard models of OR to represent the electricity market clearing. In doing so, we ensure that our representation of the market clearing follows real markets closely. Due to the very tight links of technical and economic characteristics with mathematics, OR models are a suitable tool for including more details about the technology (to represent physical limits) and economic parameters (cost curves, demand patterns, etc.) of the energy systems being modelled. Due to the technical components, energy models are referred to as a domain in engineering. As described above, the models are based on OR methods linked to economic theory and principles. The "engineer" in this setting should thus be understood as the applied scientist rather than the technology researcher and developer (Cooper, 1958).

Getting back to aspect five of what energy economics does—planning, policy and performance of the industries (Bhattacharyya, 2019)—energy system modelling can make a powerful contribution to analysing, reviewing, and improve the sector's performance. Models can be used to explore the impact of policies and targets, and can also support the formulation of intermediate goals of political targets (Süsser et al., 2021). Whereas in many economic disciplines and in parts of energy economics, the goal is set and we can be certain about the result of introducing a specific mechanism, energy system analysis and modelling can provide pathways to and details of required changes, and thus this comes one step before policy choices for incentivising specific changes. An additional contribution is to provide economics research with guiding thresholds, shadow prices, and the welfare implications of policies and policy instruments.

Paper B develops a system model to identify the trade-off between hydrogen and electricity infrastructure to connect OEHs. Whereas the main insights are related to overall capacities and allocations in connecting lines to surrounding countries, we can also learn about the cost of hydrogen and electricity in this closed setup. The evaluation of different scenarios that reflect priorities allows us to determine which of them comply with political targets for emission reduction and hydrogen production. In contrast to the more system-focused approach in *Paper B*, *Paper C* confirms the views of the economics literature by showing that the suggested bidding zones result in a more cost-reflective setup. The interdisciplinary approach of limiting the system through economic and technical approaches using mathematical tools and techno-economic modelling serves the needs of the current analysis of OEHs.

CHAPTER 3
Towards the Implementation of Offshore Energy Hubs

Part II of this thesis presents three research articles that are relevant to the overarching research questions. The thesis deals with the topics presented above, in Section 2.1, and uses the methods of Section 2.2. To provide background on each article's contribution to the research questions, the following paragraphs summarise the studies and findings separately. In Sections 3.1 and 3.2, I collect the findings and relate them to the questions with the help of the three articles. The chapter closes with a summary of the work's contributions and a discussion of both the results and the methods in Section 3.3, and some more subjective perspectives on the research in Section 3.4.

Paper A: Risks, Strategies, and Benefits of Offshore Energy Hubs

In the first paper, I explore the vision of using OEHs to exploit offshore wind potential in northern Europe. These projects are led mainly by industry and have quickly taken a spot in political discussions at the national and European levels. Until now, it has remained an open question what an OEH will look like in detail: What technologies will it be home to? How will it be integrated into the markets? And can it fulfil the promise of improving decarbonisation?

In this paper, I first develop a scheme to structurally review and assess the value of OEHs along four dimensions: technology, economics, environment, and society. The scheme is based on multi-criteria analysis and picks up common criteria for assessing renewable energy projects (Ilbahar et al., 2019; Wang et al., 2009; Wilkens, 2012). I apply it to survey literature in the context of OEHs planned in the North and Baltic Seas. However, the survey shows that the literature on this specific topic is still scarce. I extend the literature search and connect findings from related research on topics such as offshore grids, interconnectors, and sector coupling. On the basis of the survey, I summarise and rate the performance of the projects, finding that the idea is based on immature offshore technologies and that high financial risk will be transferred to society due to the character of public infrastructure projects. I also find that offshore projects present an opportunity to overcome acceptance problems onshore and to enhance the interconnection between electricity markets and systems. In a final assessment and evaluation, I conclude that open questions remain about the design of the hub itself, its system integration, and the economic framework around it. The relevant considerations are (i) the lack of information on environmental benefits and impact, (ii) the high financial risk, (iii) a strong reliance on coordinated planning, (iv) pure dependence on technology as the solution for energy system transformation, and (v) the lack of comparison with alternative solutions, such as enhancing distribution, small-scale resources, and the creation of behavioural incentives for participation.

Paper B: How to Connect Energy Islands?

The second paper explores the idea of connecting OEHs via both electricity and hydrogen infrastructures, because electrolysers are one of the technologies envisioned to be placed on those OEHs. So far, the literature holds that offshore placement depends on the relationships among electricity prices onshore, electrolyser expenses, and cable costs (Singlitico et al., 2021).

In this paper, we investigate in detail the trade-off between integrating OEHs via electricity and via hydrogen infrastructure. We set up a combined capacity expansion and electricity dispatch model to determine how the system evolves under given cost assumptions and location preferences. We use the North and Baltic Sea projects as a case study and assume that three OEHs will be operational far from shore in 2030. All currently planned offshore wind farms are clustered along the coasts, and the way they will be connected to the existing system is part of the optimisation. The case study comprises four parts: (i) a business-as-usual case without hydrogen infrastructure around OEHs, (ii) a case allowing electrolysis only on the OEHs, not onshore, (iii) an open-investment scenario with cable and hydrogen infrastructure allowed both at landing points and offshore, and (iv) a reference to the planned projects as presented by COWI (2021).

We find that the electricity system benefits from interconnection with the OEHs, and that there is a strong interdependence between distance to shore and investment in offshore electrolyser capacity. In the case study, when electrolysers are allowed both onshore and offshore, offshore electrolysis is fed solely by the resources around the OEHs and a meshed grid evolves around the close-to-shore offshore wind parks to feed the onshore electrolysers. We observe that there is a possibility that nuclear power and biomass could serve as fuel for electrolysers. Lastly, the capacity investments in electrolysers are very sensitive to hydrogen prices but less to carbon prices. In addition, the onshore grid as it is currently planned for 2030 is relatively congested close to shore, and expansions by up to 20% will increase the use of RES by 5%.

Paper C: Electrolysis as a Flexibility Resource on Energy Islands

The third paper further develops the idea of OEHs as flexibility providers. The hubs are meant to facilitate offshore sector integration by combining offshore wind energy with power-to-x technologies and storage.

We investigate the operation of electrolysers on OEHs by first assessing the potential flexibility contribution of the electrolyser and then analysing different market integration strategies for the islands. We develop a two-stage stochastic optimisation model to find a cost-efficient dispatch for an integrated day-ahead and balancing electricity market. To apply and verify the model, we set up a case study for the North and Baltic Seas projects, assuming a set capacity of offshore electrolysers commissioned by 2030 and 2040 (COWI, 2021; North Sea Wind Power Hub, 2020). For the market integration of the OEHs, we align our approach to the current debate and compare the case of a single offshore bidding zone to a case in which the OEH is integrated into a home market zone (Kitzing & Garzón González, 2020). We find that electrolysers on OEHs will run at low capacity factors and provide flexibility in 26%–30% of their runtimes. In addition, offshore electrolysers produce more hydrogen when allocated to an offshore bidding zone. This is driven by the lower electricity costs in these zones, and thus they earn higher profits. We conclude that combining offshore wind with electrolysers on an OEH will depend on additional economic incentives if their main role is to be the delivery of balancing flexibility.

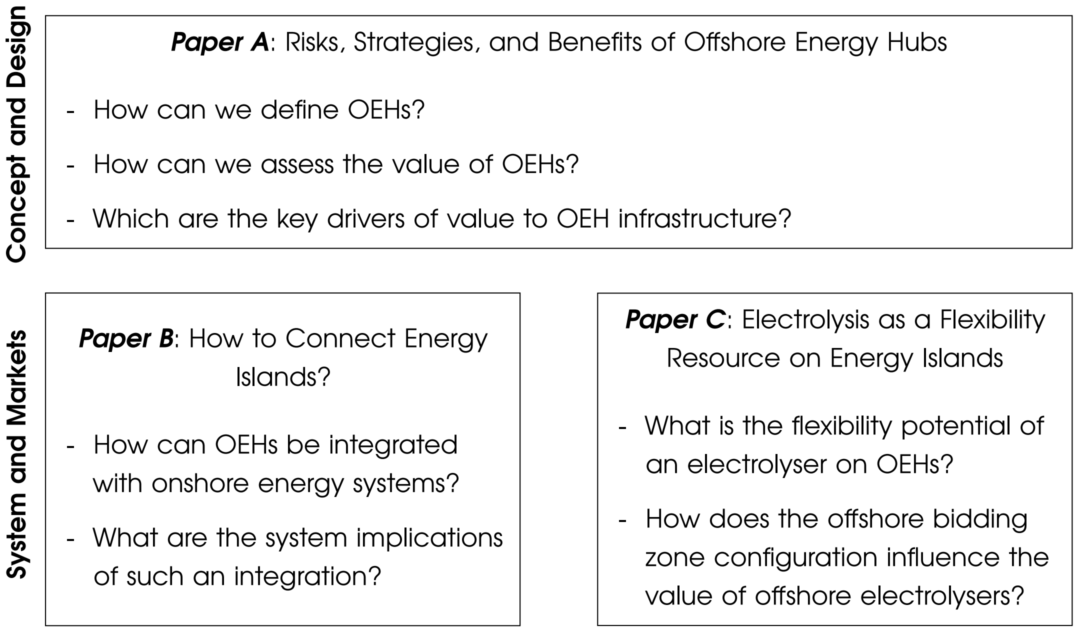


Figure 3.1. Overview of the different papers and their research questions.

The three papers described above contribute to the discussion of OEH design and development, and each individual paper has its own focus and research question. Figure 3.1 gives an overview of the research questions underlying each of the studies. In the following two sections, I combine their findings to present insights into the two overarching research questions.

3.1 Drivers and Challenges for the Development

The first research question concerns the development process for OEHs and asks what the main technological, environmental, economic, and societal drivers and challenges are, and what their impact is on offshore electrolysis. The envisioned projects are very ambitious with regard to both the timeline and the needs for technical innovation. On the role of *technology*, all three papers find that the currently envisioned technology mix for OEHs is too expensive to compete with other flexibility sources and conventional hydrogen production, due to its immaturity. A usable mix would only materialise with lower technology costs or higher CO_2 or hydrogen prices. The discussed OEH projects are part of the first large-scale roll-out, however, which makes them expensive and challenging. The progress of technology thus influences the system benefits and the competitiveness of OEHs.

As for *environmental* challenges and drivers, *Paper A* highlights the chance that OEHs will increase carbon emissions in the short run because of CO_2-intensive construction and the relocation of processes far from demand and existing infrastructure. *Paper B* shows that the future electricity mix will be highly dependent on available offshore resources to reduce emissions. In addition, *Paper C* confirms this finding and adds that emission-free hydrogen production is guided by market and system design.

From an *economic* perspective, there are many possible obstacles to the development of OEHs. Although the offshore and hydrogen strategies used by the EU have set the first goals for a fossil-free energy system, there are not yet specific economic frameworks. In *Paper C*, we discuss the role of bidding zone configurations, an aspect of market design, and show their importance for capturing the desired value of conversion, flexibility provision, or hydrogen. *Paper B* and *Paper C* both assume that the operation and ownership of offshore grids will be feasible and attractive, but there is no consensus yet on how to proceed and speed up a successful implementation. Combined interconnected solutions are disconnected from the current planning procedures. At the moment, the gas and electricity sectors work separately and so do the various national system operators. To converge on an integrated energy system across borders, coordinating efforts must be increased, as suggested by Dedecca et al. (2019).

Societal drivers include current onshore acceptance issues (*Paper A*) and the prospect of more affordable electricity prices in the future (*Paper C*). Overall, the technology must become economically viable and sustainable to satisfy society's desire for just access to cheap electricity. Whether the OEH projects can achieve this cannot be answered here, but the findings of *Paper B* and *Paper C* suggest that the current radial connections of offshore RES and the use of onshore electrolysis are only part of the solution, and must be complemented with novel approaches. When we continue the expansion of offshore wind even farther from the coasts, cost-efficient network extension will develop into a meshed structure at sea. *Paper B* highlights how offshore electrolysis can play a role in far-away electricity production to supply affordable and clean fuel for hard-to-decarbonise sectors. Yet the economic framework and the viability of offshore electrolysis are uncertain.

Offshore electrolysers and OEHs are a new, untested element to be integrated into energy systems, and this poses a challenge. For offshore electrolysers, we can observe that they are built at moderate sizes (*Paper B*) and run at capacity factors of 50%. Whereas *Paper B* helps us answer questions about sizing and siting, we assumed a fixed electrolyser capacity in *Paper C* that is 90% smaller than the endogenously determined size. In addition, an endogenous system expansion leads to much better interconnection of offshore generation and conversion assets through large-scale investments into cable capacity (*Paper B*). Future OEHs and their system integration and design will be sensitive to hydrogen prices but not so much to CO_2 prices (*Paper B*). The technical infrastructure and cable connection also influence the mode of operation and the availability of electricity for hydrogen production. The uncertainty about system development as a driver of and challenge for OEHs connects to the second research question. In the following section, I summarise key insights into system configuration and market design for offshore electrolysis.

3.2 System Configuration and Market Design for Offshore Electrolysis

The second research question asks how system configuration and market design influence the value of electrolysis on OEHs. First, system configuration and market design influence each other. If technology is set up, it should be integrated and used efficiently. On the other hand, the market design invites investments in some technologies more than others. OEHs are currently a vision, and it remains important to explore various options to guide their implementation. From the three studies in this project, we can derive some initial indications about trade-offs and driving factors for offshore electrolysis.

In general, *Paper A* gives a clear indication that immature technology and lack of economic frameworks for the hubs pose a risk. To provide initial insights, *Paper B* assumes nodal pricing to reflect the scarcity of generation and network bottlenecks in costs, and investigates how a system with onshore and offshore electrolysis could develop over time. The results suggest that the system is likely to integrate close-to-shore wind farms and to build electrolysers at small gigawatt sizes close to the links between onshore and offshore electricity cables (so-called landing points) to harvest excess electricity. *Paper B* further shows that OEHs can be integrated with onshore electricity systems via offshore wind farms rather than directly. In this way, OEHs can become importers of offshore wind energy in periods of strong wind and still deliver electricity to onshore systems directly when close-to-shore production is low. This finding follows a body of literature analysing future connections of wind energy and concluding that combined grid solutions such as Kriegers Flak will become more relevant (see, e.g., Weichenhain et al., 2019 and Marten et al., 2018).

The study in *Paper B* is based on nodal pricing, which takes into account bottlenecks in the system for pricing. Currently, prices in Europe are set in zones, which in an ideal case would be designed to reflect bottlenecks as zonal boundaries. Recent debates shed light on the problem that the existing zones may not reflect network constraints well enough (ACER, 2022). With increasing activity offshore and the common approach of integrating wind farms into their home countries' or owner countries' market zones, we would move further from nodal prices. We see in *Paper C* that this could lead to high-cost congestion management measures. To investigate the role of OEHs in this setting and learn more about the impact of bidding zone configurations, we compare the influence of HBZ and OBZ (see Section 2.1.2) on the value of electrolysers offshore. The results show that we generate more hydrogen due to lower prices with OBZs and limit the mismatch between market results and network-feasible allocations. Besides the production of hydrogen, electrolysers can serve as flexibility assets. Technically, electrolysers are capable of delivering system services to increase system stability, something they can also do when located on OEHs. In our stylised two-stage market of day-ahead and balancing markets, we observe that the use of electrolysers for flexibility is not yet the main reason for installing them. However, if flexibility provision is to become a main task of electrolysers in the system, this can be incentivised by improving economic support.

Linking the results of *Paper B* and *Paper C*, there is a system mismatch between the endogenously determined system configuration of *Paper B* and the exogenous system used for analysis in *Paper C*, which is the current planning basis for the European projects (COWI, 2021; North Sea Wind Power Hub, 2020). The main difference between the two systems is the cable capacity connecting the OEHs to shore or to offshore wind clusters. Whereas *Paper B* finds a well-interconnected system suggesting cable connections from the OEHs via offshore wind farms, *Paper C* bases its analyses on direct connections between OEHs and a few market zones that already integrate their offshore wind power. This neglects the possibility of supplying electrolysers on OEHs with offshore wind energy from sources other than close-by wind farms directly connected to the hub. The stronger interconnection between offshore assets, as suggested by solving the combined dispatch and capacity expansion model, finds a higher usage rate of offshore electrolysers. This can be attributed to two factors:[8] first, we allow better integration of the OEHs, and second, we include onshore grid constraints as a limit on the use of RES for direct electricity consumption.

The main findings on how the system configuration and market design influence the value of electrolysis on OEHs are summarised in the following five points:

- Market design and system configuration influence each other heavily (*Paper A*).
- Enforcing specific rules for system design implies a preference for electricity or hydrogen infrastructure (*Paper B*).
- Market zones and grid bottlenecks influence the siting of electrolysers (*Paper B* and *Paper C*).
- Bidding zone configuration affects the role of hydrogen production on OEHs (*Paper C*).

[8] We use the same data set on generation capacity and RES availability, and cost parameters provide the same starting point.

- Offshore electrolysis' provision of flexibility in today's system is not yet competitive (*Paper C*).

3.3 Contribution and Discussion

The following section presents the contributions to the literature in a condensed form and then discusses the methodological shortcomings and the role of the assumptions. The articles contribute to the still very small body of scientific literature on OEHs and offshore sector coupling. Besides discussing the lessons to be considered for projects in the North and Baltic Seas, I can raise the individual findings to a higher level and deliver the following broad contributions:

- A generic definition of OEHs that is not bound to a European context and that can help in the development of similar projects in other parts of the world (*Paper A*).
- A framework for analysing possible OEH projects in any location (*Paper A*).
- Mathematical frameworks for assessing the impact of integrating OEHs to energy systems (*Paper B*, *Paper C*).
- The suggestion to align market design to the technical and economic characteristics of the system (*Paper C*).
- Further resulting contributions:
  - Landing points for electricity cables from offshore wind farms are currently more attractive for electrolysis than pure offshore electrolysis (*Paper B*).
  - The location of OEHs invites some offshore electrolysers and hydrogen production rather than pure electricity-focused operations (*Paper B*).
  - Hydrogen production at the centre of wind farms in areas with high wind potential is economically viable under current and currently projected costs (*Paper B*).

Figure 3.2 combines these contributions in a visual summary. Each paper discusses OEHs from a different angle and is associated with specific topics of energy infrastructures. The scope of the papers varies between theory and implementation-oriented research and targets economic and technical aspects.

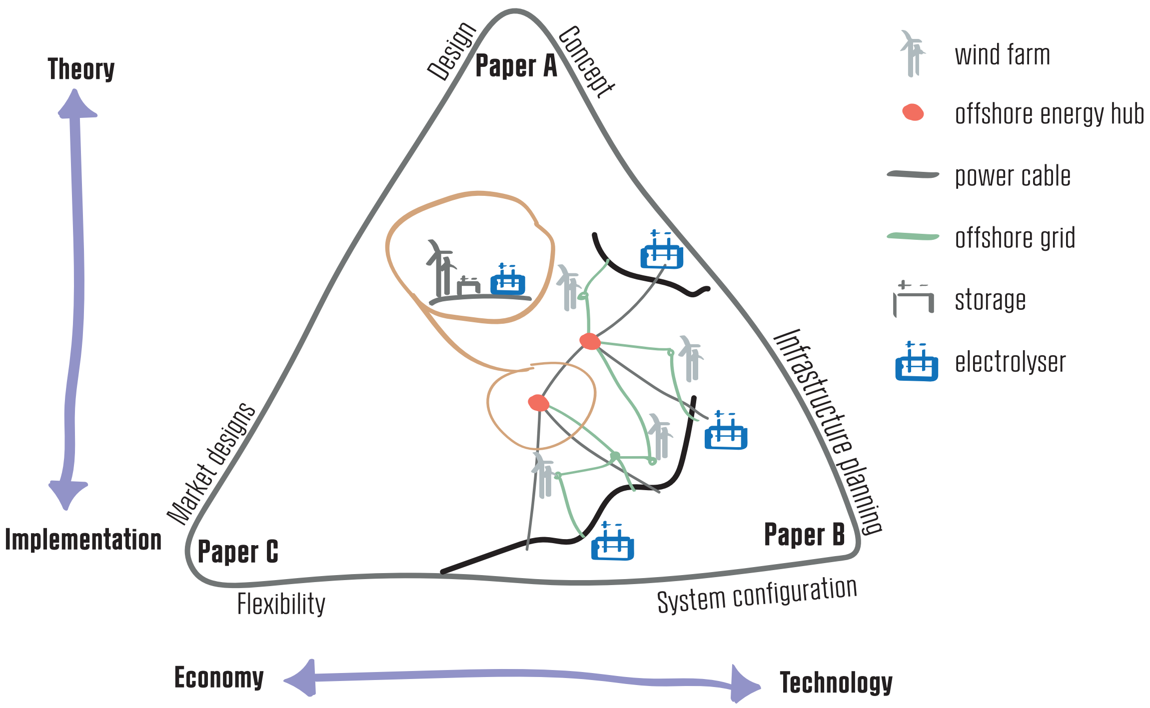


Figure 3.2. Graphical summary of the contributions.
Source: Author's illustration.

These contributions are based on stylised models and assumptions. In the remainder of this section, I discuss and reflect on these assumptions and the methods used in the thesis.

In *Paper A*, I use multi-criteria analysis to survey the literature. This is a well-recognised method in multiple fields. I base the survey criteria on a review by Ilbahar et al. (2019), who screened assessments of renewable energy projects and summarised suitable criteria. However, the list of investigated criteria is not exhaustive. To fill this gap, a systematic literature review should be conducted in the future to comprehensively assess the influence of different criteria.

Paper B and *Paper C* apply energy system modelling to answer the research questions. These studies rely heavily on current cost data and assumptions about future development. The assumptions on the future system for both studies originate in the TYNDP 2020 data set, which was developed by stakeholders in the gas and electricity sectors to map future system needs. Because of its industry connection, it may have a bias toward the role of gas and electricity infrastructure, which we controlled for only by upwardly adjusting capacities if they were already too low today. Projects investigating fully renewable energy systems, such as openEntrance (see Auer et al., 2020), call for much higher renewable energy capacities than the data set we used, which would affect the sizing, siting, and role of electrolysers due to greater RES availability. We have taken the assumptions about costs from various sources, but mainly the PyPSA data set by Hörsch et al. (2018). The future price of hydrogen is especially uncertain, and so is the demand. Many of the other assumptions about costs have already been disrupted by the current energy crisis, which is also likely to change the boundary conditions for OEH projects. Further investment in renewable energy projects is increasingly important to recover affordable energy prices, and that may include the development of such offshore hubs. With the recent developments in energy and resource prices and inflation, however, the deployment of these technologies will face higher costs. The interplay among these developments is neither reflected or tested in this thesis; together with social and behavioural components, this is one of the frequently noted shortcomings of many models (Fodstad et al., 2022; Süsser et al., 2022). In the papers presented here, the goal and impact of policies are more important than details of behaviour, and we argue that the findings serve their purpose of informing policymakers about system design and market setups.

On another level, the applied models and underlying mechanisms are based on neoclassical economic theory, which some argue has shortcomings for the economy of the future. Other progressive models and theories of values may provide different results and even more urgently underline the role of society and behaviour in these problems. We retain this as a point of consideration regarding the presented results, and we do not suggest these to be the absolute and correct numbers to base plans on.

3.4 Further Perspectives on the Presented Research

This thesis was developed in a multidisciplinary research environment through frequent exchanges with industry stakeholders, in times of strong political discourse. This motivates to examine different perspectives on the research to set it into context. Following is a moderate and vaguely personal view of the output and usability of the findings.

In *Paper A*, a qualitative study forms the basis of this thesis, and the article includes a survey of the existing literature. Moving a step beyond the available findings, we find a clear lack of environmental assessments and overall sustainability research on the idea of implementing OEHs. The gains provided by large-scale offshore infrastructure for reducing greenhouse gas emissions are challenged because most of the visions entail large construction-related carbon emissions. Projects that need cross-country coordination are difficult, and capabilities and guidance involved in bringing together players from across borders influences the outcome of the project. So far, OEH projects are seen as the only option and have no competitors offshore. This implies that technology remains the only option to transform the system—an idea to consider in the light of the role of society and behaviour. Other concepts are related to empowering consumers at the household level (Lüth et al., 2020; Lüth et al., 2018; Zepter et al., 2019) and advocating for a combination of bottom-up and top-down approaches for a successful transition.

In *Paper B* and *Paper C*, we use system models that neglect behavioural and social components of the questions posed. Comparing our study to an analysis by Gea Bermúdez et al. (2021), I see a very different picture driven by the number of exogenous and endogenous decisions included in the model. Taking offshore energy hubs as a set component of a future system, we find that offshore grids and electrolysis evolve into an "optimal solution". Assuming a Europe-wide market and allowing for investment into any system component, the authors find very little relevance for offshore electrolysis Gea Bermúdez et al. (2021). The reasons for this could be manifold, not least among them cost assumptions and the lack of incorporation of learning curves and political decisions about financial support for a specific project or vision.

The current energy price crisis underlines the urgency for wind energy to replace fossil fuels, or at a minimum to reduce resource dependence and ensure energy security. OEHs do not present a quick or ad hoc way to transition to an affordable and sustainable energy system, and under changing paradigms and societal challenges the role of such projects needs to be carefully reassessed. Such public infrastructure projects are often to the burden or benefit of the consumers, a sensitive matter in times of economic instability, and it calls for an adequate governance framework for the sector to clarify the allocation of risk between involved actors. In sum, there are indications about what we can and should learn about OEH projects. The changing political and economic landscape has introduced new uncertainties to such public infrastructure projects. All the studies in this thesis hint at a value of exploiting offshore resources in a coordinated, large-scale manner. But the numbers are only indicative and are likely overestimating the value due to data and to political and economic boundaries.

CHAPTER 4
Conclusion and Further Research

Offshore energy hubs are currently being publicly discussed as a key component of the energy transition of the Nordic and Baltic region. These hubs are envisioned as exploiting the wind potential at sea for both electricity and hydrogen production. However, key questions about system design, technology mix, and market integration remain unanswered. This thesis gives insights into to two research questions with the help of three sub-projects. The first question asks about technological, economic, ecological, and societal drivers and challenges for the development of OEHs and their impacts on offshore electrolysis. The second focuses on the analysis on system and market boundaries and characteristics for offshore analysis. From the main findings of the individual articles, I gather insights into the research questions.

With *Paper A*, I provide guiding insights for future steps and identify various risks. I note five strategic considerations that will have impacts on the effects of OEHs in Europe and possibly other regions. In *Paper B*, we suggest different options for connecting the OEHs in the North and Baltic Seas by hydrogen or electricity infrastructures. We find that offshore electrolysis is preferably size matched to nearby generation capacity, and close-to-shore wind energy is best connected to the grid and onshore electrolysers. Altering hydrogen and carbon prices lead to small differences in the outcome, but it remains profitable to connect OEHs with a few selected cables and use close-to-shore wind farms for direct electricity supplies and onshore electrolysis. In *Paper C*, we show that OEHs can produce a fair amount of hydrogen due to low electricity costs offshore. A setup with offshore bidding zones further enhances this and results in a more cost-reflective market and hydrogen production price. The idea of electrolysers being used as large-scale flexibility providers under current operating costs is not attractive yet. Technically, however, flexibility services from electrolysers are possible.

The key lessons can be summarised in a few sentences. There is some risk due to financial burdens and immature technology. The lack of comparative projects and the value of a diverse approach to mixing strategies for the energy system transformation means that we cannot yet draw conclusions on the overall benefit of OEHs. Once the projects are advancing towards implementation, the system will ideally evolve into a meshed offshore grid and a technology hub with a hydrogen focus (and possibly other conversion technology as well). And finally, long-distance cables to far-offshore wind farms should be avoided to the benefit of offshore hydrogen production. Including huge offshore generation facilities in existing market zones will necessitate expensive actions to adjust the market results to the physical constraints of the power system.

The studies leave room for a lot of exciting follow-up research. Value, benefits, and costs change with the regulatory framework, market integration, and policy framework. The definition of bidding zones, for example, will define the prices at which offshore energy hubs operate, whereas regulatory frameworks for ownership and operation might in the end determine how large the consumers' share of the costs will be. The risk of failure needs to be spread among several actors or centralised on one. We will see the need to find a common framework around the shared region of the North Sea in order for people to collectively benefit and pay for the islands, their fuel, and their energy. Challenges in the groundwork of offshore energy hubs largely concern the policy framework: Subsidies or not? One operator or several for offshore electricity and hydrogen infrastructure? Who pays for the power lines, and to where? In which market will offshore generation participate? How can we mitigate uncertainty? The design of policy and regulation will strongly affect costs, benefits, allocations, and long-term profitability as we move into an unexplored region.

Besides the regulatory and market frameworks, the methodological domain can be extended as well. For the system design and capacity extension study, further analyses should include hydrogen networks in more detail (both technical and economical) and allocate hydrogen demands to regions more specifically. This will require currently unavailable data. For the market analysis, adding detail to the technical characteristics of electrolysers could indicate whether flexibility services can be provided in more than just a day-ahead and a combined balancing market. In line with previous technical studies (Zheng et al., 2022), we may see more value to flexibility from electrolysers in market stages closer to real-time.

As a further step, and moving away from specific improvements to the studies, it will be worth assessing the value of top-down approaches to the energy transition. The implementation of large-scale hubs continues to follow the current energy system's architecture, dominated by big conventional power plants. A growing stream of literature follows the idea of a bottom-up transformation of the system to empower consumers (European Commission, 2016). This idea includes the goal of matching some characteristics of renewable energy technology, such as being small-scale, distributed, decentralised and volatile, to society and the way we use energy (Friends of the Earth Europe, 2019). Roof-top PV, mid-size batteries, heat pumps, and electric vehicles together with consumer-centred tariffs and markets have been argued to support the energy transition. However, there has been no comprehensive and extensive analysis of which path to follow, whether an integrated approach combining top-down and bottom-up transformation is desirable, or how to integrate the two approaches.

Bibliography

ACER. (2022). ACER has decided on alternative electricity bidding zone configurations. https://www.acer.europa.eu/events-and-engagement/news/acer-has-decided-alternative-electricity-bidding-zone-configurations

Auer, H., Crespo del Granado, P., Oei, P.-Y., Hainsch, K., Löffler, K., Burandt, T., Huppmann, D., & Grabaak, I. (2020). Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE. *e & i Elektrotechnik und Informationstechnik*, *137*(7), 346–358. https://doi.org/10.1007/s00502-020-00832-7

Beilby, M. H. (1975). *Economics and operational research*. Academic Press.

Bhattacharyya, S. C. (2019). *Energy Economics*. Springer London. https://doi.org/10.1007/978-1-4471-7468-4

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in Europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915. https://doi.org/10.1016/j.rser.2010.11.006

Birge, J. R., & Louveaux, F. (2011). *Introduction to Stochastic Programming*. Springer New York. https://doi.org/10.1007/978-1-4614-0237-4

Brunekreeft, G., Neuhoff, K., & Newbery, D. (2005). Electricity transmission: An overview of the current debate. *Utilities Policy*, *13*(2), 73–93. https://doi.org/10.1016/j.jup.2004.12.002

Cabral, L. M. B. (2017). *Introduction to industrial organization* (Second edition). MIT Press.

Chen, Q. (2018). *Comparative Assessment of Possible Topologies of Offshore Transmission Network in the North Sea: Role ofthe North SeaWind Power Hub at the Dogger Bank* (Master's Thesis). TU Delft. Delft, the Netherlands.

Cole, S., Martinot, P., Rapoport, S., & Papaefthymiou, G. (2015). Cost-benefit analysis of a coordinated grid development in the North Sea. *2015 IEEE Eindhoven PowerTech*, 1–5. https://doi.org/10.1109/PTC.2015.7232385

Conejo, A. J., & Prieto, F. J. (2001). Mathematical programming and electricity markets. *Top*, *9*(1), 1–22. https://doi.org/10.1007/BF02579062

Cooper, W. W. (1958). Operations Research and Economics. *The Review of Economics and Statistics*, *40*(3), 195. https://doi.org/10.2307/1927407

COWI. (2021). *Cost benefit analyse og klimaaftryk af energiøer i Nordsøen og Østersøen*. https://ens.dk/sites/ens.dk/files/Vindenergi/a209704-001_cost_benefit_analyse_endelig_version.pdf

Dantzig, G. (1963). *Linear Programming and Extensions*. RAND Corporation. https://doi.org/10.7249/R366

Dedecca, J. G., Hakvoort, R. A., & Herder, P. M. (2019). The integrated offshore grid in Europe: Exploring challenges for regional energy governance. *Energy Research & Social Science*, *52*, 55–67. https://doi.org/10.1016/j.erss.2019.02.003

EEA. (2002). *Greenhouse gas emission trends in Europe, 1990-2000* (Vol. 2002:7). European Environment Agency; Office for Official Publications of the European Communities.

Egerer, J., Kunz, F., & von Hirschhausen, C. (2013). Development scenarios for the North and Baltic Seas Grid – A welfare economic analysis. *Utilities Policy*, *27*, 123–134. https://doi.org/10.1016/j.jup.2013.10.002

Energinet, Fingrid, & Statnett. (2020). *The ideal market design for offshore grids: A Nordic TSO perspective*. https://en.energinet.dk/About-our-news/News/2020/11/04/Ideal-market-design-for-ofshore-grids

Esteban, M. D., Diez, J. J., López, J. S., & Negro, V. (2011). Why offshore wind energy? *Renewable Energy*, *36*(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009

European Commission. (2016). Clean energy for all: New electricity market design: a fair deal for consumers: EU COM(2016) 860 final. https://ec.europa.eu/energy/sites/ener/files/documents/technical_memo_marketsconsumers.pdf

European Commission & THEMA Consulting group. (2020). *Market arrangements for offshore hybrid projects in the North Sea*. Publications Office. https://doi.org/10.2833/36426

Eurostat. (2019). Greenhouse Gas Emissions in the EU. https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4a.html?lang=en

Flourentzou, N., Agelidis, V. G., & Demetriades, G. D. (2009). VSC-Based HVDC Power Transmission Systems: An Overview. *IEEE Transactions on Power Electronics*, *24*(3), 592–602. https://doi.org/10.1109/TPEL.2008.2008441

Fodstad, M., Del Crespo Granado, P., Hellemo, L., Knudsen, B. R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., & Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renewable and Sustainable Energy Reviews*, *160*, 112246. https://doi.org/10.1016/j.rser.2022.112246

Friends of the Earth Europe. (2019). *Unleashing the power of community renewable energy*. https://friendsoftheearth.eu/wp-content/uploads/2019/01/community_energy_booklet_final.pdf

Gass, S. I., & Fu, M. C. (Eds.). (2013). *Encyclopedia of Operations Research and Management Science*. Springer US. https://doi.org/10.1007/978-1-4419-1153-7

Gea Bermúdez, J., Pedersen, R. B. B., Koivisto, M. J., Kitzing, L., & Ramos, A. (2021). *Going offshore or not: Where to generate hydrogen in future integrated energy systems?* https://doi.org/10.36227/techrxiv.14806647.v2

Geidl, M., Koeppel, G., Favre-Perrod, P., Klockl, B., Andersson, G., & Frohlich, K. (2007). Energy hubs for the future. *IEEE Power and Energy Magazine*, *5*(1), 24–30. https://doi.org/10.1109/MPAE.2007.264850

Gorenstein Dedecca, J., & Hakvoort, R. A. (2016). A review of the North Seas offshore grid modeling: Current and future research. *Renewable and Sustainable Energy Reviews*, *60*, 129–143. https://doi.org/10.1016/j.rser.2016.01.112

Green, R., & Vasilakos, N. (2011). The economics of offshore wind. *Energy Policy*, *39*(2), 496–502. https://doi.org/10.1016/j.enpol.2010.10.011

Hall, L. M., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. *Applied Energy*, *169*, 607–628. https://doi.org/10.1016/j.apenergy.2016.02.044

Harris, C. (2006). *Electricity markets: Pricing, structures and economics / Chris Harris*. Wiley. http://www.loc.gov/catdir/enhancements/fy0650/2006009319-d.html

Hevia-Koch, P., & Klinge Jacobsen, H. (2019). Comparing offshore and onshore wind development considering acceptance costs. *Energy Policy*, *125*, 9–19. https://doi.org/10.1016/j.enpol.2018.10.019

Hillier, F. S., & Lieberman, G. J. (2021). *Introduction to operations research* (Eleventh edition, international student edition). McGraw-Hill Education.

Holmberg, P., & Lazarczyk, E. (2015). Comparison of congestion management techniques: Nodal, zonal and discriminatory pricing. *The Energy Journal*, *36*(2), 145–166. https://doi.org/10.5547/01956574.36.2.7

Hörsch, J., Hofmann, F., Schlachtberger, D., & Brown, T. (2018). PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strategy Reviews*, *22*, 207–215. https://doi.org/10.1016/j.esr.2018.08.012

IEA. (2019). *Offshore Wind Outlook 2019*. International Energy Agency. France. https://iea.blob.core.windows.net/assets/495ab264-4ddf-4b68-b9c0-514295ff40a7/Offshore_Wind_Outlook_2019.pdf

Ilbahar, E., Cebi, S., & Kahraman, C. (2019). A state-of-the-art review on multi-attribute renewable energy decision making. *Energy Strategy Reviews*, *25*, 18–33. https://doi.org/10.1016/j.esr.2019.04.014

IPCC. (2013). *Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Ed.). Intergovernmental Panel on Climate Change. Cambridge, United Kingdom, New York, NY, USA, Cambridge University Press.

IRENA. (2021). *Renewable Power Generation Costs in 2020*. International Renewable Energy Agency. Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, *5*(8), 614–622. https://doi.org/10.1038/s41560-020-0661-2

Kaldellis, J. K., & Zafirakis, D. (2011). The wind energy (r)evolution: A short review of a long history. *Renewable Energy*, *36*(7), 1887–1901. https://doi.org/10.1016/j.renene.2011.01.002

Kellogg, R., & Reguant, M. (2021). *Energy and Environmental Markets, Industrial Organization, and Regulation*. Cambridge, MA, National Bureau of Economic Research. https://doi.org/10.3386/w29235

Kitzing, L., & Garzón González, M. (2020). Market arrangements for offshore wind energy networks. https://orbit.dtu.dk/en/publications/market-arrangements-for-offshore-wind-energy-networks

Leinfellner, W., Eberlein, G., Parthasarathy, T., Dutta, B., Potters, J. A. M., Raghavan, T. E. S., Ray, D., & Sen, A. (1997). *Game Theoretical Applications to Economics and Operations Research* (Vol. 18). Springer US. https://doi.org/10.1007/978-1-4757-2640-4

Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews*, *96*, 156–166. https://doi.org/10.1016/j.rser.2018.07.045

Luss, H. (1982). Operations Research and Capacity Expansion Problems: A Survey. *Operations Research*, *30*(5), 907–947. https://doi.org/10.1287/opre.30.5.907

Lüth, A., Weibezahn, J., & Zepter, J. M. (2020). On Distributional Effects in Local Electricity Market Designs—Evidence from a German Case Study. *Energies*, *13*(8), 1993. https://doi.org/10.3390/en13081993

Lüth, A., Zepter, J. M., Del Crespo Granado, P., & Egging, R. (2018). Local electricity market designs for peer-to-peer trading: The role of battery flexibility: The role of battery flexibility. *Applied Energy*, *229*, 1233–1243. https://doi.org/10.1016/j.apenergy.2018.08.004

Marten, A.-K., Akmatov, V., Sørensen, T. B., Stornowski, R., Westermann, D., & Brosinsky, C. (2018). Kriegers flak–combined grid solution: coordinated cross–border control of a meshed HVAC/HVDC offshore wind power grid. *IET Renewable Power Generation*, *12*(13), 1493–1499. https://doi.org/10.1049/iet-rpg.2017.0792

Meeus, L. (2015). Offshore grids for renewables: do we need a particular regulatory framework? *Economics of Energy & Environmental Policy*, *4*(1), 85–96. https://doi.org/10.5547/2160-5890.4.1.lmee

Milgrom, P. (2009). The Promise and Problems of (Auction) Market Design. https://web.archive.org/web/20140220221421/http://www.econ.northwestern.edu/seminars/Nemmers09/milgrom-presentation.pdf

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). *Integrating Renewables in Electricity Markets* (Vol. 205). Springer US. https://doi.org/10.1007/978-1-4614-9411-9

Münster, M., Moller Sneum, D., Bramstoft, R., Buhler, F., Elmegaard, B., Giannelos, S., Strbac, G., Berger, M., Radu, D.-C., Elsaesser, D., Oudalov, A., & Iliceto, A. (2020). *Sector Coupling: Concepts, State-of-the-art and Perspectives*. https://orbi.uliege.be/handle/2268/244983

Murphy, F. H. (2013). Economics and Operations Research. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of Operations Research and Management Science* (pp. 466–476). Springer US. https://doi.org/10.1007/978-1-4419-1153-7_270

Murphy, F. H., Conti, J. J., Shaw, S. H., & Sanders, R. (1988). Modeling and Forecasting Energy Markets with the Intermediate Future Forecasting System. *Operations Research*, *36*(3), 406–420. https://doi.org/10.1287/opre.36.3.406

Myerson, R. B. (1981). Optimal Auction Design. *Mathematics of Operations Research*, *6*(1), 58–73. https://doi.org/10.1287/moor.6.1.58

Myerson, R. B. (1989). Mechanism Design. In J. Eatwell, M. Milgate, & P. Newman (Eds.), *Allocation, Information and Markets* (pp. 191–206). Palgrave Macmillan UK. https://doi.org/10.1007/978-1-349-20215-7_20

North Sea Wind Power Hub. (2020). *Market setup options to integrate hybrid projects into the European electricity market*. https://northseawindpowerhub.eu/wp-content/uploads/2020/06/NSWPH-Discussion_Paper_Market-Setups-for-Hybrid-projects1.pdf

Perlin, J. (1999). *From Space to Earth: The story of solar electricity / John Perlin*. Aatec Publications.

Poudineh, R., Brown, C., & Foley, B. (2017). *Economics of Offshore Wind Power*. Springer International Publishing. https://doi.org/10.1007/978-3-319-66420-0

Ramsebner, J., Haas, R., Ajanovic, A., & Wietschel, M. (2021). The sector coupling concept: A critical review. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(4), e396. https://doi.org/10.1002/wene.396

Ringkjøb, H.-K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews*, *96*, 440–459. https://doi.org/10.1016/j.rser.2018.08.002

Roth, A. E., & Wilson, R. B. (2019). How Market Design Emerged from Game Theory: A Mutual Interview. *Journal of Economic Perspectives*, *33*(3), 118–143. https://doi.org/10.1257/jep.33.3.118

Samuelson, W. (2002). Auctions in Theory and Practice. In K. Chatterjee & W. F. Samuelson (Eds.), *Game Theory and Business Applications* (pp. 295–338). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47568-5_10

San-Miguel-Ayanz, J., Durrant, T., Boca, R., Maianti, P., Libertà, G., Artés Vivancos, T., Oom, D., Branco, A., Tomàs. Rigo, D., Ferrari, D., Pfeiffer, H., Grecchi, R., Nuijten, D., Onida, M., & Löffler, P. (2021). *Forest Fires in Europe, Middle East and North Africa 2020* (Vol. 30862). Publications Office of the European Union.

Scholten, D., Bazilian, M., Overland, I., & Westphal, K. (2020). The geopolitics of renewables: New board, new game. *Energy Policy*, *138*, 111059. https://doi.org/10.1016/j.enpol.2019.111059

Silvast, A., Abram, S., & Copeland, C. (2021). Energy systems integration as research practice. *Technology Analysis & Strategic Management*, 1–12. https://doi.org/10.1080/09537325.2021.1974376

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition*, *1*, 100005. https://doi.org/10.1016/j.rset.2021.100005

Soroudi, A. (2017). *Power System Optimization Modeling in GAMS*. Springer International Publishing. https://doi.org/10.1007/978-3-319-62350-4

Sunila, K., Bergaentzlé, C., Martin, B., & Ekroos, A. (2019). A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis. *Energy Policy*, *128*, 775–782. https://doi.org/10.1016/j.enpol.2019.01.047

Süsser, D., Ceglarz, A., Gaschnig, H., Stavrakas, V., Flamos, A., Giannakidis, G., & Lilliestam, J. (2021). Model-based policymaking or policy-based modelling? How energy models and energy policy interact. *Energy Research & Social Science*, *75*, 101984. https://doi.org/10.1016/j.erss.2021.101984

Süsser, D., Gaschnig, H., Ceglarz, A., Stavrakas, V., Flamos, A., & Lilliestam, J. (2022). Better suited or just more complex? On the fit between user needs and modeller-driven improvements of energy system models. *Energy*, *239*, 121909. https://doi.org/10.1016/j.energy.2021.121909

Trötscher, T., & Korpås, M. (2011). A framework to determine optimal offshore grid structures for wind power integration and power exchange. *Wind Energy*, *14*(8), 977–992. https://doi.org/10.1002/we.461

Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews*, *122*, 109547. https://doi.org/10.1016/j.rser.2019.109547

Vlahos, K., Kall, P., & Wallace, S. W. (1995). *Stochastic Programming: Models, Theory, and Computation* (Reprinted, Vol. 46). Wiley. https://doi.org/10.2307/2584504

Vohra, R. V. (2011). *Mechanism design: A linear programming approach / Rakesh V. Vohra* (Vol. 47). Cambridge University Press.

von Hirschhausen, C., Gerbaulet, C., Kemfert, C., Lorenz, C., & Oei, P.-Y. (2018). *Energiewende "Made in Germany"*. Springer International Publishing. https://doi.org/10.1007/978-3-319-95126-3

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021

Weibezahn, J. (2020). *Modeling an integrated energy transformation of the electricity sector* (Doctoral Thesis). Technische Universität Berlin. https://doi.org/10.14279/depositonce-10400

Weichenhain, U., Elsen, S., Zorn, T., & Kern, S. (2019). *Hybrid projects: How to reduce costs and space of offshore developments: North Seas Offshore Energy Clusters study*. Publications Office of the European Union. https://doi.org/10.2833/416539

Wilkens, I. (2012). *Multikriterielle Analyse zur Nachhaltigkeitsbewertung von Energiesystemen - Von der Theorie zur praktischen Anwendung* (Dissertation). Technische Universität Berlin. https://doi.org/10.14279/depositonce-3385

Zepter, J. M., Lüth, A., Del Crespo Granado, P., & Egging, R. (2019). Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage. *Energy and Buildings*, *184*, 163–176. https://doi.org/10.1016/j.enbuild.2018.12.003

Zhang, H., Tomasgard, A., Knudsen, B. R., Svendsen, H. G., Bakker, S. J., & Grossmann, I. E. (2022). Modelling and analysis of offshore energy hubs. *Energy*, *261*, 125219. https://doi.org/10.1016/j.energy.2022.125219

Zheng, Y., You, S., Bindner, H. W., & Münster, M. (2022). Optimal day-ahead dispatch of an alkaline electrolyser system concerning thermal–electric properties and state-transitional dynamics. *Applied Energy*, *307*, 118091. https://doi.org/10.1016/j.apenergy.2021.118091

Part II

Collection of Papers

Paper A

Alexandra Lüth

Risks, Strategies, and Benefits of Offshore Energy Hubs

A Literature-Based Survey

CHAPTER A
Risks, Strategies, and Benefits of Offshore Energy Hubs

A.1 Introduction

Offshore energy hubs (OEHs)—also called *energy islands*[1]—are being handled as a key component for the European Union's pursuit of decarbonisation targets. OEHs have so far not been a major part of research into future renewable-based energy systems. The idea originated in the European context of energy system transformation, and most examples and studies have involved European issues. However, the concept is widely applicable in any context of combining offshore and onshore energy systems at a large scale.

The vision of OEHs involves the development of large-scale assets in the sea that will allow the collection of wind energy and energy conversion and storage (North Sea Wind Power Hub, 2021). Embedded in offshore grid infrastructures, OEHs will contribute to the decarbonisation of the energy sector. The term generally refers to a combination of a large number of recent developments and system configurations moved into a new context. The main challenge in the development of these hubs is to identify the components individually and to then translate this knowledge about these components from the original context to their application to OEHs. Research into OEHs, must cover topics as for example multi-energy systems, energy hubs, integrated energy systems, smart energy systems, energy system integration, and sector coupling, and more technological elements such as high-voltage direct current systems, offshore

[1]Especially in the Danish context, energy islands should not be confused with islanded solutions onshore, where areas have their own energy supplies and are disconnected from the main electricity network, or with physical islands that aim to have fully renewable energy systems or have reached full decarbonisation, e.g. Samsø Energy Island or Madeira.

grids, energy conversion technologies, and energy storage.

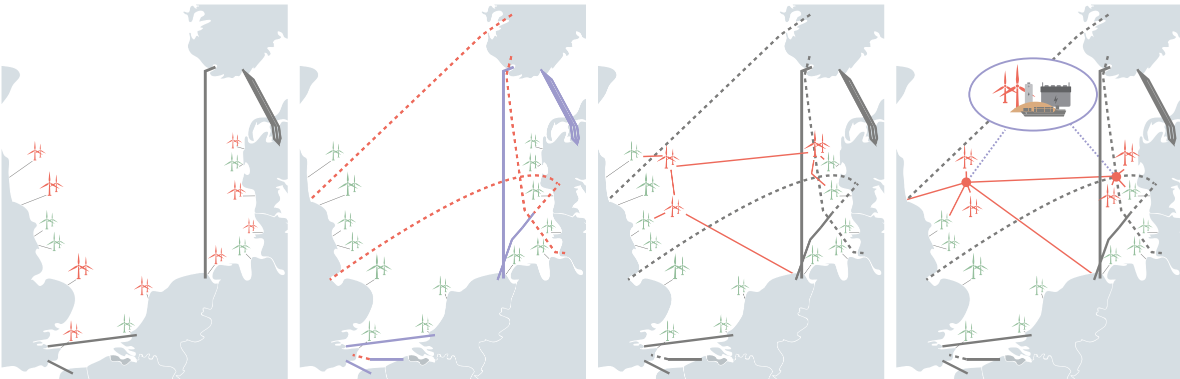
The contributions of this paper are threefold: (1) It suggests a definition of offshore energy hubs. (2) It derives a generic assessment scheme to survey the value of OEHs. (3) It applies the developed scheme to the case of the North Sea to identify the key drivers of OEH infrastructure and to point out strategic trade-offs. The definition is based on descriptions in scientific literature and project reports. The assessment scheme broadly follows the approach of multi-criteria analysis but leaves out quantitative work to focus just on the structure and criteria assessment only. Applying the scheme to the North Sea projects, I find a fair body of literature and several large research gaps. One main finding is that the concept of OEHs is built on immature offshore technologies, lacks scientific support for the construction of the hubs, and involves high technological and financial risk. On the other hand, I observe that offshore connections that serve as interconnectors, in particular, can provide value and integrate electricity systems and markets, leading to improved welfare.

The remainder of the paper is structured as follows: Section A.2 summarises the history of OEHs and presents a clear definition of them. Section A.3 describes an assessment scheme along technical, economic, ecological, and social dimensions. I then apply the scheme to survey the first planned islands in the North and Baltic Seas in Section A.4. I describe the main trade-offs that I can identify in Section A.4.5. Section A.5 summarises the value of the scheme and the key lessons.

A.2 Conceptualising Offshore Energy Hubs

Offshore energy hubs developed out of a combination of several recent movements. The discussion started when offshore wind became a key element in the decarbonisation of energy production. The first offshore windpark, *Vindeby*, was built in 1991 in the Baltic Sea and operated by the Danish company Ørsted (Bilgili et al., 2011; DONG Energy, 2017). The capacity of offshore wind has been increasing ever since, especially in Europe. More renewable energy in a system goes hand in hand with the need for more flexible resources. Using the example of the European geographic area, I can describe how OEHs evolved and how they can be defined.

Traditionally, wind farms are connected by cable to their owner's market zones; Figure A.1(a). In addition, interconnection of countries' electricity system has been constantly expanding. Interconnection, as shown in Figure A.1(b), both allows countries to benefit from cheaper resources in other countries and creates system stability. The first sea connection was built in 1961, between France and the U.K., based on high-voltage direct-current technology, and its successor is still in operation. In 2015, a goal was set of 10% electricity interconnection in Europe by 2020 (European Commission, 2015), targeting not only continental connections but also sea cables.



(a) Offshore Wind. **(b)** Interconnection. **(c)** Offshore grid. **(d)** OEHs.

Figure A.1. Development of offshore strategies and visions, from offshore generation to OEHs.
Source: Author's illustration, partially based on ENTSO-E (2021).

For offshore wind parks and interconnectors in Europe, the North and Baltic Seas quickly came into focus. Discussions of how to connect these wind farms to shore gained importance (European Commission, 2020). On the basis of the expansion of offshore wind in the North Sea and Baltic Sea, various projects[2] developed new approaches to the connection of generation to the existing grids. One leading approach was to abandon the traditional wind farm-to-owner-country (home country) and country-to-country (radial) connections by building an offshore grid in an integrated or meshed structure (Kitzing & Garzón González, 2020; Tosatto et al., 2021). Radial connections, linking one country to another, are called

[2]To name a few: PROMOTioN, Baltic InteGrid, NorthSeaGrid.

interconnectors in Europe. In home-country modes, the wind farm is connected only to the country of its owner.

In addition to simple connections to multiple countries and offshore wind installations, offshore grids can support the efficient use of offshore renewable resources (Strbac et al., 2014) and lead to higher interconnection, which supports fully renewable systems (Schlachtberger et al., 2017; Spiecker et al., 2013). This provides two main benefits: interconnection of countries and thus markets, and large-scale integration of offshore energy technologies (Gorenstein Dedecca & Hakvoort, 2016). The literature on modelling offshore grids is already improving, and a review by Gorenstein Dedecca and Hakvoort (2016) sets up a framework for assessing the different studies.

In light of discussions about building offshore grids instead of radial connections to improve system efficiency (Chen, 2018; Strbac et al., 2014), OEHs can naturally evolve at locations where the grid connects large generation to several surrounding countries and thus serve as power link islands (Kristiansen, Korpås, et al., 2018) or hubs (van der Meijden, 2016), see also Figure A.1(d). In general, an energy hub is an entity where energy conversion, storage, and conditioning take place (Geidl et al., 2007). The first vision of an offshore version of this ends the timeline in Figure A.1.

Although the idea of OEHs originated in discussions around the North and Baltic Seas, the underlying concept can be seen as a generic approach to creating flexibility around power links and generation centres both offshore and onshore. In broad terms, an OEH can be defined as follows:

> *An offshore energy hub is a fully renewable energy resource-based combination of assets that link at least two services, such as electricity generation, interconnection, and offshore storage. These services are relevant to energy system development and operation and foster decarbonisation of the energy sector while preserving the environment.*

Onshore energy and offshore energy hubs are both spaces where different energy carriers (wind, sun) are converted and stored, for example in the form of hydrogen or in batteries. In addition, different infrastructures are linked on a hub (electricity and most likely gas or heat). The main difference is the lack of direct conventional and residential load.

Projects that combine generation and interconnection are often referred to as *hybrid projects*, not to be confused with *hybrid assets*, which are infrastructure elements with the purpose of transmission and interconnection (North Sea Wind Power Hub, 2020). Examples of hybrid projects with hybrid assets are Kriegers Flak in the Baltic Sea and the Cobra Cable in the North Sea (ENTSO-E, 2016). Following this definition, OEHs can be categorised as hybrid projects, under specific market designs also be seen as hybrid assets.

A.3 Assessment of Offshore Energy Hubs

OEHs are still a theoretical concept based on a vision. Many details have not yet been fully explored, for example size, location, and technology. Since European consortia presented the first ideas in 2016 (North Sea Wind Power Hub, 2017), researchers have contributed studies of renewable offshore energy systems and their impact on markets, welfare, prices, system stability, marine ecosystems, and decarbonisation. To cluster and survey these studies around the concept of OEHs, I develop a review and assessment scheme inspired by multi-criteria assessment (MCA) and tailored towards organising and analysing literature on offshore energy infrastructure projects. The structured material can then inform an assessment. Below I describe the scheme, including a suggested workflow and the criteria for the review of OEH projects.

A.3.1 The Scheme

In general, multi-criteria analysis sets a hypothesis and evaluates a project on the basis of several criteria (Wilkens, 2012). The relevance of MCA for renewable energy projects has been recognised and summarised by Wang et al. (2009), who list many examples of such applications. Munda (2005) describes a significant driver of sustainability projects as non-monetary influences on the value of projects; that is, impacts that are hard to monetise such as intrusion, acceptance, and participation. Relevant assessment criteria are reviewed by Ilbahar et al. (2019), and I use three studies to identify common criteria: Ilbahar et al. (2019), Wang et al. (2009), and Wilkens (2012). I use the core of the presented criteria and extend them

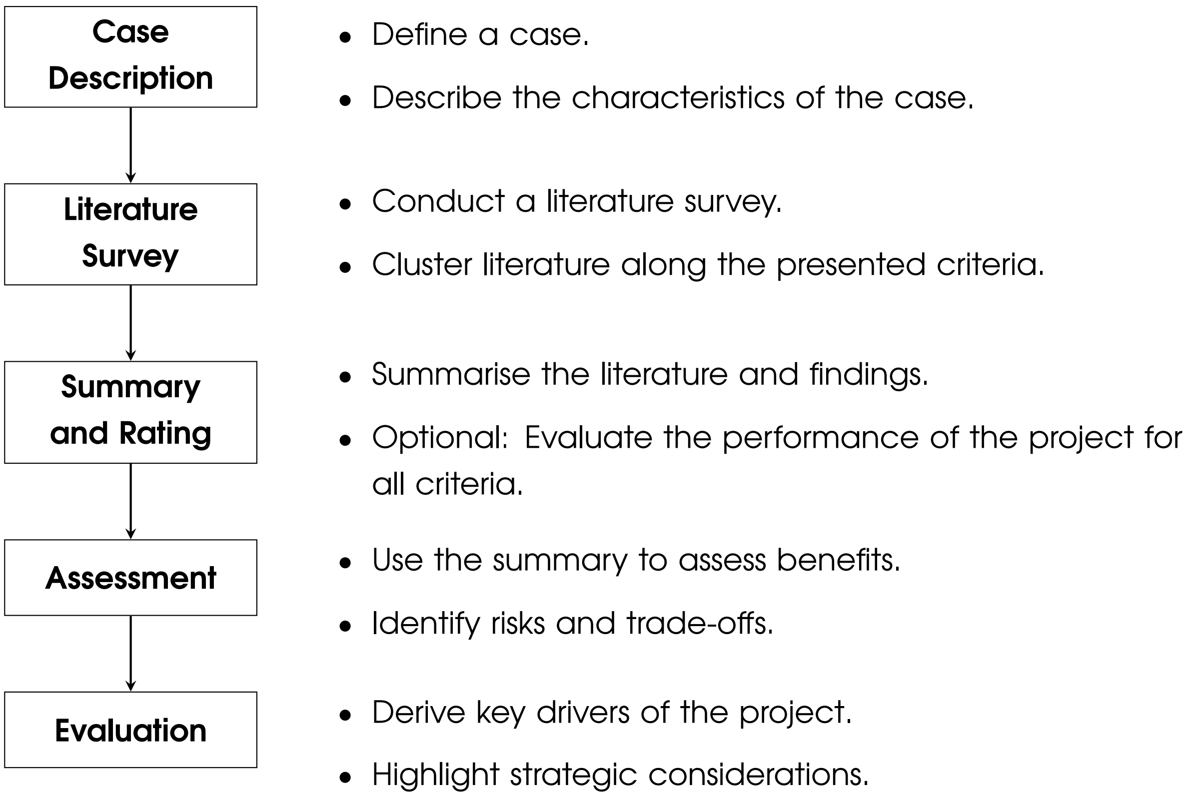


Figure A.2. Suggested workflow of the survey and assessment scheme for OEH projects.

with drivers that are specifically relevant to offshore energy infrastructure. The suggested evaluation follows a qualitative approach on an ordinal scale for each category. I suggest a workflow following Figure A.2.

The assessment starts with a definition of the case to be analysed. The second step is a literature survey to identify studies using the various assessment criteria. On this basis, the findings can be summarized, and the overall outcome for each criterion can also be rated. Then the benefits, risks, and trade-offs are identified. Finally, all these steps provide input to derive the key drivers and strategic challenges of the case. Below, I explain the criteria used to cluster and analyse the literature and the summary (steps two and three).

A.3.2 Criteria

I cluster the criteria for the survey of OEHs into the most common groups (Ilbahar et al., 2019) and define technological, economic, ecological, and societal criteria. Table A.1 presents the relevant criteria.

Table A.1. Assessment Criteria for OEHs.

Technical	**Economic**	**Ecological**	**Societal**
Efficiency	Capital cost	Biodiversity & intrusion	Acceptability
Maturity	Governance & regulation	Climate protection	Health
Operations & maintenance	Market design	Emission (reduction)	Job creation
Safety & reliability	Ownership & operation	Land use & spatial planning	Participation
	Risk & uncertainty	Resource utilisation	Social benefits & equity

I define four **technological criteria** that are likely to heavily affect the performance of OEHs. Energy projects are very technical in character and require a strong assessment of the chosen technology. This assessment can be made from system and component points of view, which lead to different insights and highlights. In line with the literature, I find that technological *maturity* can reduce the risks of a project and is thus an important factor. *Technical efficiency* drives the competitiveness and economics of the technology and must be included in any evaluation of options. Further, *safety and reliability* are relevant characteristics of the technological performance to ensure long-term stability. Last, I consider *operations and maintenance* to be key for the success: the less cost and effort, the better.

Energy projects are capital intensive and of high economic importance in today's energy dependent economies. I formulate five **economic criteria** that are relevant to assessing OEHs and their economic performance. *Capital costs* are a key value that guiding cost-benefit analyses use as input, and they thus are a criterion. When projects are operational, their economic performance depends on markets, rules, and business models. To reflect the readiness of the economic frameworks for OEH projects, I include *governance and regulation*, which provides the framework for operation and leads the way to successful implementation. One part of this is *market design*, which I include as a separate criterion in my analysis to reflect the market's readiness to absorb new models and setups. In addition, I regard business setup and *ownership and operation* as highly influential due to the allocation of costs and benefits. Last, I need to look at *economic risk and uncertainty* and assess how vulnerable the projects are.

Decarbonisation of the economy drives the transformation of the energy system and induces the expansion of offshore energy sources. Yet *emission reduction* and *climate protection* are not the only ecological criteria to consider when looking at the value of OEHs. Besides the non-negligible factors of emission reduction and climate protection, I present three more **ecological criteria**. Offshore energy project are resource intensive, use space, and intrude on untouched marine space. I stick to the most common criteria from Ilbahar et al. (2019) and add *biodiversity and intrusion*, *land use and spatial planning*, and *resource utilisation* to the above. These last three criteria cover the role of competition for space that is to be shared between nature and humans, and which must be maintained to ensure functioning ecosystems.

Last, I add five **societal criteria** to highlight the role of society as a driver or delayer of these projects. As a society, we depend heavily on energy and thrive by keeping that dependence while reducing carbon emissions to mitigate climate change. However, the transformation of this energy economy to clean sources faces significant other obstacles and has impacts in many more domains than just the technical, economic, and ecological. Besides immediate and measurable impacts like *job creation* and *social benefits and equity*, which develop alongside a transition and projects within it, there are less quantifiable indicators. Among those, I assess the effects of the projects on *health*, following the debate about climate change threatening our habitat. In addition, I value *participation* in the projects and add a factor of *acceptability* as part of this assessment.

A.4 Assessing Sustainability: Survey of European Progress

I apply the scheme and procedure described in Section A.3 to the case of the North Sea OEHs. Following the workflow, I describe my case in Section A.4.1. Section A.4.2 presents the literature survey, including all the criteria. In Section A.4.3, I summarise the literature and present an evaluation using an ordinal scale. On the basis of the summary, I describe benefits, risks, and trade-offs in Section A.4.4 and derive strategic challenges in Section A.4.5.

A.4.1 The Case of the North Sea

Europe is currently the world's leader in offshore wind: Offshore wind potentials in Europe are high in the North Sea region and thus involve many adjacent countries, such as Belgium, Germany, Denmark, the Netherlands, France, Norway, Sweden and the U.K. (Kaldellis et al., 2016). The North Sea region is not the only part in Europe to develop offshore wind power, but together with the Baltic Sea it is the frontrunner. With its offshore renewable strategy (European Commission, 2020), the European Commission formulated a clear direction for a system transformation based strongly on offshore energy systems.

The Danish government announced two *energy islands* as part of its plan for energy and industry to reach 70% reduction of CO_2 emissions by 2030.[3] The Danish transmission system operator (TSO) Energinet has also set up the *North Sea Wind Power Hub (NSWPH)* consortium[4] with the German and Dutch TSO TenneT to promote an OEH in the North Sea within the TEN-E priority corridor. This priority corridor allows for EU funding of projects of common interest (PCI).[5] Although the NSWPH is still seeking approval at the European level, the Danish government passed an agreement on details about the first island in Danish waters: 210 billion DKK, an artificial island, 3 GW offshore wind, and interconnection capacities to surrounding countries, to be in the full package operational by 2030 (Plechinger, 2021). This quickly developed into the current target of two Danish islands: one in the North Sea and one in the Baltic with 10 GW and 3 GW of wind energy connected, respectively[6]; see Figure A.3.

The Danish projects and the NSWPH are the three leading OEH projects, but the concept is also relevant to Norwegian offshore energy (Zhang et al., 2022). All the published visions and concepts follow the generic approach described in SectionA.2 and consider placing conversion

[3]cf. Klimaaftale for energi og industri mv., June 2020.
[4]See North Sea Wind Power Hub: www.northseawindpowerhub.eu.
[5]See: PCI Project Status.
[6]cf. Energistyrelsen (2022).

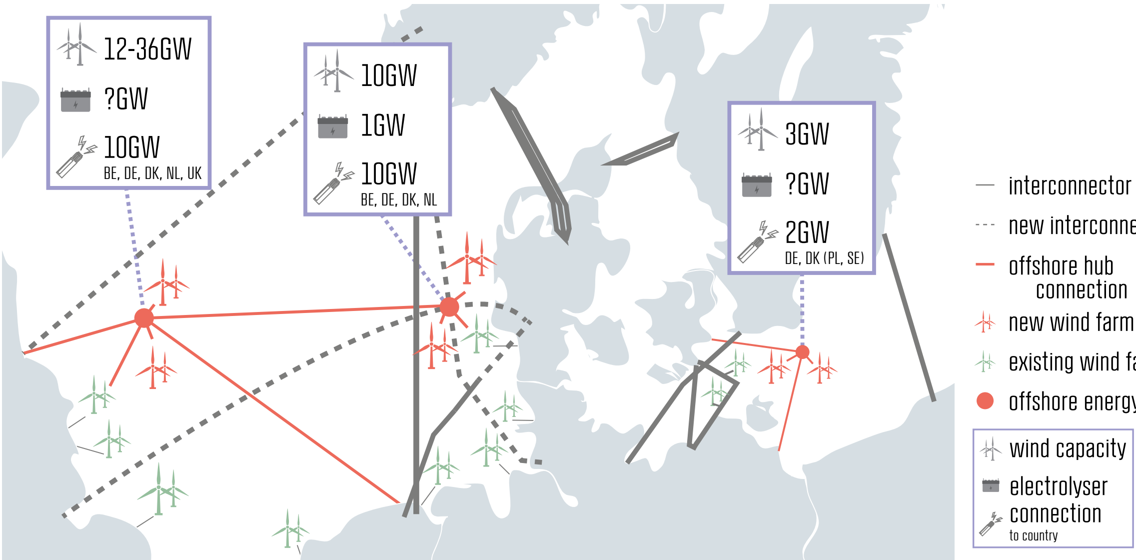


Figure A.3. Overview of current OEH projects in Northern Europe.
Source: Author's illustration based on COWI (2021) and North Sea Wind Power Hub (2021).

and storage technology close to offshore wind. Analyses to assess the value, determine the design, help with policymaking and ensure acceptance have not been conducted for the case of the North Sea.

A.4.2 Survey

Sections A.4.2.1–A.4.2.4 provide the literature survey. I considered literature on OEHs, offshore grids, energy islands[7], and offshore wind. Wherever I saw a lack in the literature or was able to identify related topics (for example, studies of sector coupling onshore), I used reviews on renewable energy projects in general. The following sections present the literature that is relevant to assessment and evaluation. I structure the literature along the criteria.

A.4.2.1 Technological Criteria

The technological dimensions of an OEH include all the technologies the hub is home to or that are connected or related to it. In some locations, it might be more suitable to create a large wind power hub, while

[7]This term is often used for islands in the process of decarbonisation, or islanded energy systems, which led to a fair number of studies being disregarded.

others invite solar power, conversion, and storage technologies as well. In designing an OEH, the technical dimensions must include the technical devices installed at and around the OEH, their components and the means of connection and operation of those, and the system aspects. From a technological point of view, plans for sizing, mode of connection, and operation can depart from the conventions on energy hubs, virtual power plants, and multi-energy systems to determine an efficient path.

An OEH is placed offshore and must be connected to the land. As nodes in a meshed offshore grid would invite OEHs to evolve, there is a technical overlap between the design of offshore grids and hubs (Chen, 2018) creating synergies. High-voltage grid connections and low-inertia setups are suitable characteristics that can support OEHs where wind energy is harvested and collected at a central point (Misyris et al., 2020). Studies show that the implementation of high-voltage direct current power lines can support the efficient design and operation of offshore grids (Vrana & Torres Olguin, 2015).

Although there seems to be a clear consensus that OEHs are the point to harvest offshore wind energy to send it bundled into an offshore grid, there is no straightforward plan for what technology should be installed in addition to this. North Sea Wind Power Hub (2021) envisions an OEH that is home to electrolysers that produce hydrogen; Siemens, Ørsted and ITM develop technology to produce hydrogen inside wind turbines, which would turn each hub into not only a power link but a hydrogen link island (fch, 2021). Batteries, pump storage, and gas tanks can also provide flexibility, though their shape, size, and combination have not yet been investigated and have never been tested offshore. The first results point to electricity-only production being the most valuable element to invest in, but the combined operation can also be valuable and feasible (McDonagh et al., 2020). OEHs in operation are expected to support the decarbonisation of the energy sector and create a reliable and resilient infrastructure for operating a fully renewable system. The technology at the hub must be chosen with respect to technical interaction and operation to keep costs and maintenance needs low while still extracting the most value from the new investment. If wind power alone is not considered definitive of OEHs, insights from research into sector coupling and system integration can help us determine the specific characteristics of other power generation, storage, and conversion technologies (Zheng et al., 2022a, 2022b).

Efficiency. Conversion technology in the form of power-to-x transforms electricity into a different energy carrier such as hydrogen, heat, fuel, or other green gases (Buttler & Spliethoff, 2018; Koj et al., 2019). Whenever electricity is converted, losses occur, and there is a different target market with other characteristics and a design that affects the costs, benefits, and long-term profitability of the installed technology. With the possibility of electrolysers producing hydrogen on OEHs (potentially even inside wind turbines), the economics of hydrogen production (Glenk & Reichelstein, 2019) will significantly influence size, operations, locations, and connection to gas and other network infrastructures. The first studies show a trade-off between direct electricity use via cable connections and hydrogen conversion. Gea Bermúdez et al. (2021) find that cables are preferred over hydrogen production if there is no specific hydrogen demand. Yet electrolysers can be a flexibly operated asset (Zheng et al., 2022a) and serve as balancing component (Lüth et al., 2022).

Maturity. Component-wise, offshore wind is a rather mature technology (Jiang, 2021), but offshore electrolysis is still in its pilot phase (Brauns & Turek, 2020; Buttler & Spliethoff, 2018). Battery storage and other conversion processes have not yet been tested offshore, nor can they be related to any similar offshore constructions. Mere oil and gas platforms are similar in their foundations to one of the options suggested in COWI (2021), however. Those platforms are well tested around the world and are more explored than sand constructions.

Operations and Maintenance. Many needed add-ons to offshore wind technology do not yet exist as commercial hardware. Although energy generation potential is much stabler and higher offshore, there are disadvantages as well: high costs of engineering, installation, and maintenance, a need for grid expansion, and limited access (Bilgili et al., 2011).

Safety and Reliability. Early research indicates that a meshed grid structure in the sea can stabilise renewable-based systems, but there is not yet enough evidence to achieve additional flexibility through the creation of technology-combining offshore hubs as Figure A.4 suggests. The value of shifting those hubs to other highly interconnected areas, such as onshore landing points, must be gauged before support is granted, similar to what Singlitico et al. (2020) suggest.

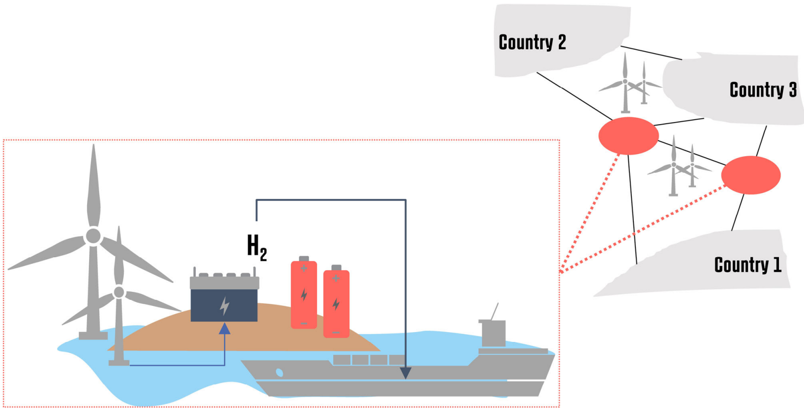


Figure A.4. An illustrative example of an OEH hosting electrolysers, and storage technology in proximity to offshore wind farms.
Source: Author's illustration.

A.4.2.2 Economic Criteria

The most efficient technical composition is not always the most economical. The reasons can be manifold, including lack of policy support, cost of technology, market rules, and varying demand or supply. To combine the technical and economic dimensions for an overall efficient outcome, different trade-offs must be weighed and policy and technology aligned. Although the technical dimension will decide the choice of technology, the economic framework must ensure profitability and will need to guide implementation.

Capital Costs. In the specific case of OEHs, the combined strengths of hubs and integrated offshore networks let them outcompete radial and home-country connections (Weichenhain et al., 2019). Coordinated planning puts pressure on the profitability of large infrastructure investments in offshore grids: meshed grids lead to lower system costs but depend heavily on coordinated planning and building efforts (Gea-Bermudez et al., 2018; Gea-Bermúdez et al., 2020; Kristiansen, Muoz, et al., 2018).

So far, the development of offshore wind, grids, and interconnection has remained a national task (Gorenstein Dedecca & Hakvoort, 2016). In an international setup, difficulties arise among partners, and the task is to develop along national or regional plans (Dedecca et al., 2019). Traber et al. (2017) argue that the harmonisation and coordination of efforts at grid expansion and capacity building can have a positive long-term effect on costs in general and with respect to offshore infrastructure projects. The interconnection of strong markets with asymmetric renewable capacity is seen as stabilising prices in the connected markets (Alavirad et al., 2021).

Market Design. Besides coordinated planning and investment, market design is crucial to success. Market design for OEHs includes questions about the owner and operator of the technology, pricing rules, and regulatory frameworks. Due to the renewable energy generation around hubs, the market design will need to be in line with the requirements for a high-renewables scenario that unites intermittent resources with necessary levels of competition while either addressing or avoiding market failures (Djørup et al., 2018; Newbery et al., 2018). OEHs are just another component of the renewable offshore setting and add a layer of complexity to it. In general, two market design options seem to have become the leading concepts: designs of home markets and offshore bidding zones have been suggested by Weichenhain et al. (2019) on behalf of the European Commission. These designs have been taken up by the North Sea Wind Power Hub (2020) and were commented on by Energinet et al. (2020). Using a system model, Kitzing and Garzón González (2020) evaluate the two designs for a Danish energy island with only wind energy connected and conclude in favour of the offshore bidding zone. Lüth et al. (2022) add hydrogen production to the OEH and show that offshore bidding zones lead to more hydrogen production at slightly higher prices offshore while keeping onshore production prices stable. Singlitico et al. (2021) present an approach to determining offshore production costs for hydrogen and show that offshore placement can make the wind parks more economical through peak shaving production, and Gea Bermúdez et al. (2021) argue that offshore hydrogen production will play a small role.

Governance and Regulation. Offshore wind projects need grid access, and instead of farm-to-shore connections, a meshed infrastructure could support the integration of far-out offshore wind projects. The regulatory models for grid infrastructure to connect such farms differs around Europe and even around the Baltic Sea (Sunila et al., 2019) and North Sea (Meeus, 2015). Whereas harmonisation towards a more competition-oriented model would enhance offshore wind projects, harmonisation towards a TSO-model that supports advanced connection planning would be more beneficial (Meeus, 2015). The key to the overall process is the alignment of rules. Due to the variety of policies around Europe, Sunila et al. (2019) suggest the creation of a supra-national TSO for a pure offshore grid: a single operator of an offshore grid as a fully European solution under EU regulations, rather than coordinated and cooperative approaches.

Ownership and Operation. Today, the literature focuses on economic regulation and market design for offshore wind, offshore grids, and OEHs with solely wind energy connected. An OEH might include further technologies such as batteries, pump storage, or electrolysers. For now, there is evidence supporting offshore grids and wind power islands being valuable to the system, which highlights the need to allow for their emergence through market design and economic regulation. Kitzing and Garzón González (2020), among others, provide give first indications to how this can be done. Meeus (2015) and Sunila et al. (2019) present ideas for addressing the difficulties about the ownership and operation of the offshore grid. In the presence of conversion technologies such as electrolysers, the economics of renewable energy conversion (Glenk & Reichelstein, 2019) will be a key driver. The produced and available quantity of hydrogen affects the path to integration with the gas sector, which will add a market- and system-integration component to the energy island. This will open a discussion about several modes of operation and ownership structures surrounding power-to-x, which is already heavily discussed for onshore technologies (Xiong et al., 2021).

Risk and Uncertainty If technical analysis shows value added by storage or electrolysers on OEHs, the economic framework will need to catch up with this recommendation and investigate whether support schemes are needed to extract this value. Financing schemes for offshore wind energy have shown that the support scheme influences the deployment of the technology and must be adjusted to the rolled-out capacity (González & Lacal-Arántegui, 2016). Yet the whole concept of OEHs is new and carries uncertainty in many variables.

A.4.2.3 Ecological Criteria

OEHs are being developed to help decarbonise the energy sector, and it seems like an obvious assumption that the projects will support green transition. To verify this, I summarise existing studies on the environmental and ecological impacts of OEHs. Each OEH will be different and thus have a different impact.

Resource Utilisation. The first studies evaluate various foundations, such as the construction of sand islands, caisson islands, or a platform (North Sea Wind Power Hub, 2019). Denmark has decided to use sand islands (Plechinger, 2021). COWI (2021) evaluated the impact of each foundation type on behalf of the Danish Energy Agency and found that the chosen sand island solution (sænkekasseø) has the highest additional carbon footprint due to material production. An analysis of repurposing existing offshore infrastructure has not been conducted.

Emission Reduction and Climate Protection. Effects of construction might counteract the environmental benefits of an energy island. The concrete industry has the largest industry emissions in Denmark (Klima, Energi- og Forsyningsministeriet, 2020), and scarcity of sand must also be considered for large new constructions (Gavriletea, 2017; Padmalal & Maya, 2014). Cables as a connecting infrastructure emit electromagnetic waves, and phases of construction can disturb natural processes in the sea.

Land Use and Spatial Planning. Onshore wind installations quickly led to public opposition, and offshore wind farms were thought to resolve problems of visual and environmental impact, planning, and spatial considerations (Haggett, 2008). The same considerations will be necessary with respect to OEHs. The more technology is added to the hub, the more we will need to move these industrial centres away from the shore. But though this might resolve public acceptance problems, there are trade-offs in space, ecosystems, biodiversity, health implications, and the use of resources. The sea seems to provide large space and unlimited possibilities, but sea area is limited, and marine spatial planning is important when increasing offshore activities: shipping, energy transport and generation, tunnel and bridge building, fishing and farming, and maintenance of natural recreation areas and ecosystems. With OEHs, we add capacity for energy transport, generation, and storage. Well-designed incentives from policymakers are needed to prevent congestion but use the available space for infrastructure efficiently.

Biodiversity and Intrusion. Species under the sea and in the air are affected by the building of offshore wind generation (Soukissian et al., 2017). The phase of construction threatens submarine wildlife, such as fish and molluscs, the most. Once construction is completed, new ecosystems can evolve, and they have done so in the North Sea (Gimpel et al., 2020). However, the long-term effects remain unknown. Frequent interventions in the sea can destroy newly developed ecosystems, another point of consideration in the construction of energy islands and the choice of size.

A.4.2.4 Societal Criteria

In the long term, society will profit from investments in clean energy technology. An energy-driven lifestyle can help societies develop while preserving air quality and lowering environmental pressures. Whether investments in OEHs will benefit society as a whole depends on all the aforementioned criteria: technical and economic design and consideration of environmental impacts.

Acceptability. Offshore wind parks developed fast when land for onshore wind became scarce (Esteban et al., 2011) and public opposition to onshore wind farms increased (Haggett, 2008). The more stable winds and greater space justified the expansion of offshore installations. Public acceptance is said to increase with participation (Tobiasson & Jamasb, 2016), which in the case of OEHs will not take place. The costs of acceptance are high, and in some cases outweigh the high investment costs (Hevia-Koch & Klinge Jacobsen, 2019).

Health. There is a wide consensus that cleaner air is beneficial to health (Kampa & Castanas, 2008; Pope et al., 1995). Energy production and industry-related CO_2 emissions reached a global high of 36.3 gigatonnes in 2021, with coal in the lead (IEA, 2021). These record emissions contribute about 40% of global greenhouse gas emissions and thus add significantly to air pollution. The adoption of clean technology will have health benefits for the population and reduce health system pressure and costs.

Participation. OEHs have met high acceptance rates so far, but acceptance is not triggered by participation, as in other top-down approaches. Local and decentralised concepts often encourage acceptance through participation (Dumitrescu et al., 2022; Lavrijssen & Carrillo Parra, 2017; Lüth et al., 2018). Centralised, large-scale projects such as OEHs and large offshore wind farms, centralised power-to-x plants, and big storage units do not involve citizens but require infrastructure development, which may affect acceptability.

Social Benefits and Job Creation. Under current designs, the costs and benefits of these integrated solutions will be distributed unevenly unless policy implements reallocation mechanisms (Egerer et al., 2013; Huppmann & Egerer, 2015; Konstantelos et al., 2017). The allocation of costs and benefits among the ideally involved parties influences willingness to participate. In the absence of re-allocation mechanisms parties may withdraw and bring significant disadvantages to the overall venture. Job creation in the renewable energy sector was seen early on as an economic opportunity (Lehr et al., 2012; Wei et al., 2010), and it is needed to compensate for job losses in the sectors that are replaced (Oei et al., 2020).

A.4.3 Summary and Rating

The first studies of OEHs discuss problems and aim to answer to emerging questions about the concept. The above details of the criteria defined in Section A.3 present a first glance at the obstacles to developing OEHs in the North Sea. To summarise the main items in the different categories, I structure them along the scheme presented in Table A.4.3. Column 2 indicates the performance of the concept in my assessment. I add a note to explain the assessment and add the references. In the assessment, I distinguish five levels: poor ($--$), weak ($-$), fair ($\circ$), good ($+$), and excellent ($++$).

For the technological assessment, I conclude that the North Sea OEHs can benefit from efficient wind energy conditions offshore and fairly mature offshore wind technology. Interconnection allows for stabilisation of the broader European electricity system, but experience with interconnected wind farms is limited and the system stability impact is not large, so I rate it at fair quality but not excellent. Sector integration is one of the main work items at the moment and suffers from immaturity despite great working examples. Offshore electrolysis is not operational at all, and the immature technology poses a high risk and relies on heavy effort for operations and maintenance work. Overall, the maturity and efficiency of offshore wind energy invite to proceed with the project. First experiences with system stability through increased interconnection have provided good prospects. Immature offshore technology, increased maintenance effort, and lack of sector coupling success are currently the weak points of the projects.

As for the economic parts of the projects, most are not yet defined or adjusted to facilitate system and market integration. Governance and regulation in Europe are focused on onshore national solutions, but for OEHs they will need to extend their scope to multinational solutions and legal frameworks. I therefore cannot evaluate the performance of OEHs with respect to governance, ownership, operation, and market design, and I highlight the fact that changes and future frameworks for offshore energy projects will influence the success of OEHs. The lack of guiding European regulations is one source of risk and uncertainty. High capital costs, immature technology, and lack of experience are others where the projects rate as poor.

The ecological assessment has a two-part result. The use of offshore wind as a resource leads to emission reduction and faces less competition in offshore areas, and I will need less space and technology offshore due to higher capacity factors. However, OEHs with added hub components have undefined benefits. Construction of the island itself creates additional carbon emissions, and construction and decommissioning destroy and intrude into new areas. In addition, the construction of an OEH requires resources, and if existing offshore constructions from oil and gas extraction in the North Sea cannot be repurposed, additional emissions will be created.

Society benefits largely from reduced emissions improving health, and the transition to renewable energy creates many jobs along coasts and at harbours in the North Sea region. The long-term effects on society and equity cannot be evaluated yet, but early insights propose that welfare will increase. A public project is a risk that society might need to pay for if it fails. The acceptability of OEHs can be rated as sufficiently high because of their distance from humans. General participation in OEHs is low, and this presents a downside.

Overall, for each category, I can identify benefits and weaknesses. I use the assessment to derive opportunities, risks, and barriers in the following sections.

Table A.2. Summary and rating of the OEH project idea and concept.

Criteria		Note	Related Literature
Technological			
Safety & reliability	○	Evolve where there is large wind potential and connection to offshore grids: can also stabilise the offshore grid.	Misyris et al. (2020) and Vrana and Torres Olguin (2015)
Maturity			
Offshore wind	+	Semi-mature technology	Esteban et al. (2011), Jiang (2021), and Sun et al. (2012)
Offshore electrolysis	−−	No experience, onshore counterparts are also still under development.	Brauns and Turek (2020), Buttler and Spliethoff (2018), and Singlitico et al. (2021)
Sector integration	−	Gaining experience.	McDonagh et al. (2020), Münster et al. (2020), and Ramsebner et al. (2021)
Interconnection	○	The first hybrid project started in 2021, interconnectors are not fully exploited yet.	Marten et al. (2018), Schlachtberger et al. (2017), Spiecker et al. (2013), and Strbac et al. (2014)
Efficiency			
Wind energy	+	Offshore wind locations provide better wind conditions.	Bilgili et al. (2011) and Snyder and Kaiser (2009)
Electrolysis	−	Conversion losses.	Buttler and Spliethoff (2018), Koj et al. (2019), and Zheng et al. (2022a, 2022b)
operations & maintenance	−	Higher efforts and costs offshore, centralised setup for better access.	Bilgili et al. (2011) and Sun et al. (2012)

−− poor, − weak, ○ fair, + good, ++ excellent

Criteria		Note	Related Literature
Economic			
Capital cost	−−	High cost, unexplored concept, high dependence on interest rates, sustainability influenced by choice of financing source (green finance).	Dedecca et al. (2019), Glenk and Reichelstein (2019), González and Lacal-Arántegui (2016), Green and Vasilakos (2011), Jansen et al. (2022), and Traber et al. (2017)
Ownership & operation	○	Undefined structures, landowner: state, remaining part to be determined.	Singlitico et al. (2020), Sunila et al. (2019), and Xiong et al. (2021)
Governance & regulation	○	Uncertain legal definition of OEHs will shape division of tasks.	Jansen et al. (2020), Meeus (2015), and Sunila et al. (2019)
Market design	○	Not developed, bidding zone configuration influences prices significantly.	Alavirad et al. (2021), Djørup et al. (2018), Kitzing and Garzón González (2020), Newbery et al. (2018), and Weichenhain et al. (2019)
Risk & uncertainty	−−	High risk and uncertainty due to interest rates, immature concept, international collaboration, geopolitics.	Martini (2021), Puka and Szulecki (2014), Scholten et al. (2020), and Vakulchuk et al. (2020)

−− poor, − weak, ○ fair, + good, ++ excellent

Criteria		Note	Related Literature
Ecological			
Emissions (reduction)			
Offshore wind	+	Key resource for energy transition.	
Energy island	−	Undefined climate benefit, construction emissions high.	COWI (2021)
Land use/spatial planning	+	Use of untouched space, trade-off between repurposing and new construction not considered.	Snyder and Kaiser (2009)
Resource utilisation	−	Intense sand use, large land fill.	COWI (2021), Gavriletea (2017), Padmalal and Maya (2014), and Plechinger (2021)
Climate protection	−	Additional benefit of artificial hub not visible.	
Biodiversity & intrusion	−	Seen as an intrusion into new areas; animals and plants can adapt and benefit, but construction and decommissioning causes destruction.	Gimpel et al. (2020) and Soukissian et al. (2017)
Societal			
Acceptability	++	Increased acceptability due to avoiding close interaction with humans.	Esteban et al. (2011), Haggett (2008), Hevia-Koch and Klinge Jacobsen (2019), and Tobiasson and Jamasb (2016)
Social benefits & equity	○	Lighthouse project will receive public funding, risk for costs exceeding benefits, first insights propose welfare increase.	Huppmann and Egerer (2015) and Konstantelos et al. (2017)
Health	○	Renewable energy improves air quality; long-term environmental consequences on whole biosphere unexplored.	Kampa and Castanas (2008) and Pope et al. (1995)
Participation	−−	No immediate participation.	Tobiasson and Jamasb (2016)
Job creation	+	Northern Europe maintains and expands renewable energy industry.	Lehr et al. (2012), Oei et al. (2020), and Wei et al. (2010)

−− poor, − weak, ○ fair, + good, ++ excellent

A.4.4 Assessment

OEHs open for **opportunities** for market integration across countries and for enhancing the interconnection of the involved parties to construct the island. Interconnection has been shown to stabilise the energy systems and belongs to the priority corridors for the electricity grid (European Commission, 2021). The bundling of offshore resources with the development of grid infrastructure can allow the harvesting of large unexploited offshore resources while being less space-intense. If OEHs include energy storage and power-to-x, possibilities for energy system integration and emerging synergies can be exploited. High acceptance rates and job creation further support the North Sea project.

I can also identify **barriers** to OEH projects. Those can be overcome with policy instruments, advances in research and development, and education and participation. The first step, of identifying the ideal location for an OEH, is one barrier. The topic is highly political (Puka & Szulecki, 2014), and there is a risk of strong disagreement or opposition. In the current situation, there is a front runner (the North Sea region) and bottom-up development (industry-led) in a system with mostly top-down regulation, similar to the case of offshore grids (Härtel et al., 2018). But in addition to geopolitics and interference with national plans, there is a lack of clear guiding research on this topic. The first studies have emerged discussing offshore grids and market design, but the smart approach to OEHs has not been explored. Policymakers rely on information and education by researchers to create sustainable and valuable frameworks for the development of such projects. In the absence of studies, progress will be slowed by lack of information.

Just as for offshore grids, the optimal design of OEHs within an integrated grid structure might not be reachable in the desired shape: integrated and coordinated planning over a long time horizon brings **risks** and uncertainty, and it is not required by any regulation such as TEN-E (Gorenstein Dedecca et al., 2017). An integrated system design including well-connected OEHs can have significant benefits. But to reach this ideal scenario, the planning and building must be integrated to ensure that the gradual development of large-scale infrastructure is well coordinated, and the optimal layout can be reached by passing several milestones. Radial connections might still need to be part of the system (Gorenstein Dedecca et al., 2017). Other risks involve financing strategies, influences of interest rates and on immature electrolysis and offshore technology, and uncertainty about the acceptability of supporting such large infrastructure projects.

A.4.5 Strategic Considerations for Offshore Energy Hubs

In planning OEHs, I can use this analysis to identify key drivers and strategic considerations. Although the time frame for the Danish lighthouse OEH is set, the joint international project for the North Sea is still pending. Research into a generic design as well as the specific design of the Danish OEH is still scarce, but future projects will be able to make use of the lessons of the first project in Danish waters. In general, there are still challenges to be faced in the case of the North Sea as well as for other hubs. Research might provide answers quickly, but at this point, I draw qualitative conclusions from my analysis, with five main strategic considerations to be answered for such projects. These are derived from trade-offs that I identified following the assessment scheme.

1. ***Significance of environmental benefits***
   Although the vision of OEHs is in line with the decarbonisation of the energy sector to mitigate climate change, it remains unclear how much they will contribute to the targets of reducing emissions. One critical element is the construction phase: The building sector produced 40% of global emissions in 2019 (UNEP & IEA, 2019) and must follow a targeted decarbonisation strategy to make the hub more beneficial than an onshore setup without the need for extensive foundation building, steel, or concrete (Padmalal & Maya, 2014). It has not been determined whether OEHs will have a positive impact through the creation of a circular economy (Geissdoerfer et al., 2017).

2. ***System benefits vs. sunk investments***
   Once OEHs are operational, they are expected to provide flexibility, cheap electricity, and grid services, and to stabilise a fully renewable energy system. The first calculations show that OEHs have significant benefits for energy systems in operations and decarboni-

sation (North Sea Wind Power Hub, 2021; Weichenhain et al., 2019). However, if one or more of the current assumptions (e.g., degree of connection, scale of power connected, capacity of interconnection) do not hold, this picture will change. The impact of changing assumptions remains unclear, but the risk of sunk investments being borne by society is large. In addition, markets and governance will play crucial roles. Unless policy sets the right framework, market failures (Newbery et al., 2018) could harm profitability.

3. ***Reliance on coordinated planning***
An OEH is to a large extent an add-on to the discussion of meshed grid infrastructure in the sea. The first research on meshed offshore grids has shown that such a project is highly sensitive to uncoordinated planning (Gea-Bermúdez et al., 2020; Gorenstein Dedecca et al., 2017). An OEH has common grounds with regulated system operators and players in the competitive market, i.e. electricity generators. In addition, the projects involve many countries in the beneficial cases of reaching high levels of interconnection. Economies of coordination will be a crucial factor to make investment, ownership and operation turn into a coherent system. Policymakers will need to assess the trade-off of unbundling versus economies of coordination carefully.

4. ***Technology as solution***
Technological change and adaptation have been the main focus lately in the discussion of mitigating climate change. Although many solutions are technical, the social and behavioural aspects of tackling decarbonisation are often overlooked. IEA (2010) presents an outlook on CO_2 emission reduction in which end-use fuel switching and efficiency gains contribute a share of 43%, which includes end-users. The impact of a rebound effect is not consistently quantified, except for direct rebound being within a range of 0%–30% (Sorrell et al., 2009). The rebound effect in energy clearly counteracts the full exploitation of efficiency gains and increases the need for additional energy. Strong policies in favour of energy saving and energy sufficiency (Darby & Fawcett, 2018) do not clearly support the current layout of the energy industry, but they can relieve society of expenses for the decarbonisation of the energy sector.

5. ***OEHs as the best or the only option?***
   OEHs represent a clear vision. In the light of strong challenges and the long path to full decarbonisation, this vision gives a clear picture of a solution. Beyond the image of OEHs, the vision becomes blurry. The options for hitting the targets have not been compared extensively. Although the focus of OEH creation is bundling centralized generation and storage, other ideas aim at a solution aligned with the distributed and decentralised character of renewable energy generation: local and small solutions such as peer-to-peer electricity markets (Giotitsas et al., 2015; Lüth et al., 2018). It is unclear whether these approaches are alternatives or complements. Small solutions at the end-user level or close to it can lead to greater acceptance due to larger involvement (Morstyn et al., 2018).

A.5 Conclusions and Outlook

The vision of OEHs will move quickly towards implementation. It remains unclear what the first hub will look like and whether the concept will take off and expand outside Northern Europe or remain a one-time project. Investment costs are high, so societal benefits need to be large too.

This paper presents a scheme for assessing OEHs. It discusses aspects of the planning, structuring, and design processes and suggests a literature-based analysis of the relevant criteria using a multi-criteria assessment-inspired structure. I find that OEHs combine immature technologies that pose a high risk. The economic frameworks are not yet settled and make evaluations of the benefits impossible. Experience, however, does suggest that the economics of those projects drives their viability. The capital costs for large infrastructure projects (and the necessary research and development) are high and the payback is uncertain. The development of economic frameworks and regulations is the key to creating an efficient technical system: not only the cost of each item, but the regulatory framework and market design are decisive in creating a long-term, sustainable OEH. For the environment and society, the impact is scattered: the project might lead to cleaner energy supplies and better health and job situations, but it could damage wild waters in ways that are not measurable today. Although optimal technical and economic solutions seem feasible, the environmental aspects will determine the impact on the overall target of a socially acceptable, cheap, environmentally sustainable transition to a low-carbon society.

The survey of the literature on OEHs leads to conclude with five strategic considerations, including the trade-offs we must make in deciding to implement OEHs: The environmental benefits are unidentified, and there is no benchmark to measure alternatives against. The project is subject to high financial risk, and we cannot preclude sunk investments, especially due to reliance on coordinated planning. The ideas presented on OEHs suggest that technology will be the path to energy system transformation by letting us move projects out of areas with little public acceptance. This stands against other solutions, however, and no studies have compared systemic approaches, such as decentralised and behavioural solutions, to centralised technological ones. These considerations arise in part due to the lack of research and therefore of present research opportunities. That said, further research must address the characteristics and design features outlined here to further identify profitable and smart specifics. This could involve analysing the choice of technologies, the design and specifications of those technologies, and the operational modes. This survey lists a large number of questions and items to be researched, and Table A.4.3 gives these insights in terms of evaluations of the North Sea projects that allow for improvements. The chosen method allowed for a guiding, forward-looking survey of the light body of literature to create an overview and definition of the topic. In the presence of more studies, a more structured, full-scale literature review might be able to build up common knowledge. However, in this study I do contribute by providing a solid and structured groundwork to begin working on knowledge gaps.

References

Alavirad, S., Mohammadi, S., Golombok, M., & Haans, K. (2021). Interconnection and generation from a North Sea power hub – A linear electricity model. *International Journal of Electrical Power & Energy Systems*, *133*, 107132. https://doi.org/10.1016/j.ijepes.2021.107132

Bilgili, M., Yasar, A., & Simsek, E. (2011). Offshore wind power development in Europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*, *15*(2), 905–915. https://doi.org/10.1016/j.rser.2010.11.006

Brauns, J., & Turek, T. (2020). Alkaline Water Electrolysis Powered by Renewable Energy: A Review. *Processes*, *8*(2), 248. https://doi.org/10.3390/pr8020248

Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440–2454. https://doi.org/10.1016/j.rser.2017.09.003

Chen, Q. (2018). *Comparative Assessment of Possible Topologies of Offshore Transmission Network in the North Sea: Role ofthe North SeaWind Power Hub at the Dogger Bank* (Master's Thesis). TU Delft. Delft, the Netherlands.

COWI. (2021). *Cost benefit analyse og klimaaftryk af energiøer i Nordsøen og Østersøen*. https://ens.dk/sites/ens.dk/files/Vindenergi/a209704-001_cost_benefit_analyse_endelig_version.pdf

Darby, S. J., & Fawcett, T. (2018). *Energy sufficiency: an introduction: Concept Paper*. https://www.energysufficiency.org/static/media/uploads/site-8/library/papers/sufficiency-introduction-final-oct2018.pdf

Dedecca, J. G., Hakvoort, R. A., & Herder, P. M. (2019). The integrated offshore grid in Europe: Exploring challenges for regional energy governance. *Energy Research & Social Science*, *52*, 55–67. https://doi.org/10.1016/j.erss.2019.02.003

Djørup, S., Thellufsen, J. Z., & Sorknæs, P. (2018). The electricity market in a renewable energy system. *Energy*, *162*, 148–157. https://doi.org/10.1016/j.energy.2018.07.100

DONG Energy. (2017). The World's First Offshore Wind Farm Is Retiring. https://stateofgreen.com/en/partners/orsted-a-global-leader-within-green-energy/news/the-worlds-first-offshore-wind-farm-is-retiring/

Dumitrescu, R., Lüth, A., Weibezahn, J., & Groh, S. (2022). Prosumer Empowerment through Community Power Purchase Agreements: A Market Design for Swarm Grids. *Economics of Energy & Environmental Policy*, *11*(1). https://doi.org/10.5547/2160-5890.11.1.rdum

Egerer, J., Kunz, F., & von Hirschhausen, C. (2013). Development scenarios for the North and Baltic Seas Grid – A welfare economic analysis. *Utilities Policy*, *27*, 123–134. https://doi.org/10.1016/j.jup.2013.10.002

Energinet, Fingrid, & Statnett. (2020). *The ideal market design for offshore grids: A Nordic TSO perspective*. https://en.energinet.dk/About-our-news/News/2020/11/04/Ideal-market-design-for-ofshore-grids

ENTSO-E. (2016). TYNDP Project Data 2016. https://www.entsoe.eu/publications/tyndp/tyndp-2016/

ENTSO-E. (2021). Grid Map. https://www.entsoe.eu/data/map/

Esteban, M. D., Diez, J. J., López, J. S., & Negro, V. (2011). Why offshore wind energy? *Renewable Energy*, *36*(2), 444–450. https://doi.org/10.1016/j.renene.2010.07.009

European Commission. (2015). At least 10% electricity interconnection in EU by 2020. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_15_4486

European Commission (Ed.). (2020). *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future: COM(2020)741/F1*. https://ec.

europa.eu/transparency/regdoc/rep/1/2020/EN/COM-2020-741-F1-EN-MAIN-PART-1.PDF

European Commission. (2021). Trans-European Networks for Energy | Energy. https://ec.europa.eu/energy/topics/infrastructure/trans-european-networks-energy_en?redir=1#priority-corridors

fch. (2021). Offshore hydrogen from shoreside wind turbine integrated electrolyser. https://www.fch.europa.eu/project/offshore-hydrogen-shoreside-wind-turbine-integrated-electrolyser

Gavriletea, M. (2017). Environmental Impacts of Sand Exploitation. Analysis of Sand Market. *Sustainability*, *9*(7), 1118. https://doi.org/10.3390/su9071118

Gea Bermúdez, J., Pedersen, R. B. B., Koivisto, M. J., Kitzing, L., & Ramos, A. (2021). *Going offshore or not: Where to generate hydrogen in future integrated energy systems?* https://doi.org/10.36227/techrxiv.14806647.v2

Gea-Bermudez, J., Pade, L.-L., Papakonstantinou, A., & Koivisto, M. J. (2018). North Sea Offshore Grid - Effects of Integration Towards 2050. *2018 15th International Conference on the European Energy Market (EEM)*, 1–5. https://doi.org/10.1109/EEM.2018.8469945

Gea-Bermúdez, J., Pade, L.-L., Koivisto, M. J., & Ravn, H. (2020). Optimal generation and transmission development of the North Sea region: Impact of grid architecture and planning horizon. *Energy*, *191*, 116512. https://doi.org/10.1016/j.energy.2019.116512

Geidl, M., Koeppel, G., Favre-Perrod, P., Klockl, B., Andersson, G., & Frohlich, K. (2007). Energy hubs for the future. *IEEE Power and Energy Magazine*, *5*(1), 24–30. https://doi.org/10.1109/MPAE.2007.264850

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gimpel, A., Stelzenmüller, V., & Haslob, H. (2020). *Offshore-Windparks: Chance für Fischerei und Naturschutz*. Johann Heinrich von Thünen-Institut. https://doi.org/10.3220/CA1580724472000

Giotitsas, C., Pazaitis, A., & Kostakis, V. (2015). A peer-to-peer approach to energy production. *Technology in Society*, *42*, 28–38. https://doi.org/10.1016/j.techsoc.2015.02.002

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, *4*(3), 216–222. https://doi.org/10.1038/s41560-019-0326-1

González, J. S., & Lacal-Arántegui, R. (2016). A review of regulatory framework for wind energy in European Union countries: Current state and expected developments. *Renewable and Sustainable Energy Reviews*, *56*, 588–602. https://doi.org/10.1016/j.rser.2015.11.091

Gorenstein Dedecca, J., & Hakvoort, R. A. (2016). A review of the North Seas offshore grid modeling: Current and future research. *Renewable and Sustainable Energy Reviews*, *60*, 129–143. https://doi.org/10.1016/j.rser.2016.01.112

Gorenstein Dedecca, J., Hakvoort, R. A., & Herder, P. M. (2017). Transmission expansion simulation for the European Northern Seas offshore grid. *Energy*, *125*, 805–824. https://doi.org/10.1016/j.energy.2017.02.111

Green, R., & Vasilakos, N. (2011). The economics of offshore wind. *Energy Policy*, *39*(2), 496–502. https://doi.org/10.1016/j.enpol.2010.10.011

Haggett, C. (2008). Over the Sea and Far Away? A Consideration of the Planning, Politics and Public Perception of Offshore Wind Farms. *Journal of Environmental Policy & Planning*, *10*(3), 289–306. https://doi.org/10.1080/15239080802242787

Härtel, P., Mende, D., Hahn, P., Bley, A., & Rohrig, K. (2018). North Seas Offshore Network (NSON): Challenges and its way forward. *Journal of Physics: Conference Series*, *1104*, 012004. https://doi.org/10.1088/1742-6596/1104/1/012004

Hevia-Koch, P., & Klinge Jacobsen, H. (2019). Comparing offshore and onshore wind development considering acceptance costs. *Energy Policy*, *125*, 9–19. https://doi.org/10.1016/j.enpol.2018.10.019

Huppmann, D., & Egerer, J. (2015). National-strategic investment in European power transmission capacity. *European Journal of Operational Research*, *247*(1), 191–203. https://doi.org/10.1016/j.ejor.2015.05.056

IEA. (2010). *Energy Technology Perspectives: Scenarios and Strategies to 2050*. International Energy Agency. https://www.iea.org/reports/energy-technology-perspectives-2010

IEA. (2021). *Global Energy Review: CO2 Emissions in 2021*. International Energy Agency. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

Ilbahar, E., Cebi, S., & Kahraman, C. (2019). A state-of-the-art review on multi-attribute renewable energy decision making. *Energy Strategy Reviews*, *25*, 18–33. https://doi.org/10.1016/j.esr.2019.04.014

Jansen, M., Duffy, C., Green, T. C., & Staffell, I. (2022). Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea. *Advances in Applied Energy*, *6*, 100090. https://doi.org/10.1016/j.adapen.2022.100090

Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020). Offshore wind competitiveness in mature markets without subsidy. *Nature Energy*, *5*(8), 614–622. https://doi.org/10.1038/s41560-020-0661-2

Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. *Renewable and Sustainable Energy Reviews*, *139*, 110576. https://doi.org/10.1016/j.rser.2020.110576

Kaldellis, J. K., Apostolou, D., Kapsali, M., & Kondili, E. (2016). Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. *Renewable Energy*, *92*, 543–556. https://doi.org/10.1016/j.renene.2016.02.018

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental pollution (Barking, Essex : 1987)*, *151*(2), 362–367. https://doi.org/10.1016/j.envpol.2007.06.012

Kitzing, L., & Garzón González, M. (2020). Market arrangements for offshore wind energy networks. https://orbit.dtu.dk/en/publications/market-arrangements-for-offshore-wind-energy-networks

Klima, Energi- og Forsyningsministeriet. (2020). Ny samarbejdsaftale: Aalborg Portland forpligter sig til mindst 660.000 ton CO2-reduktioner. https://kefm.dk/aktuelt/nyheder/2020/sep/aalborg-portland

Koj, J. C., Wulf, C., & Zapp, P. (2019). Environmental impacts of power-to-X systems - A review of technological and methodological choices in Life Cycle Assessments. *Renewable and Sustainable Energy Reviews*, *112*, 865–879. https://doi.org/10.1016/j.rser.2019.06.029

Konstantelos, I., Pudjianto, D., Strbac, G., de Decker, J., Joseph, P., Flament, A., Kreutzkamp, P., Genoese, F., Rehfeldt, L., Wallasch, A.-K., Gerdes, G., Jafar, M., Yang, Y., Tidemand, N., Jansen, J., Nieuwenhout, F., van der Welle, A., & Veum, K. (2017). Integrated North Sea grids: The costs, the benefits and their distribution between countries. *Energy Policy*, *101*, 28–41. https://doi.org/10.1016/j.enpol.2016.11.024

Kristiansen, M., Korpås, M., & Farahmand, H. (2018). Towards a fully integrated North Sea offshore grid: An engineering–economic assessment of a power link island. *Wiley Interdisciplinary Reviews: Energy and Environment*, *7*(4), e296. https://doi.org/10.1002/wene.296

Kristiansen, M., Muoz, F. D., Oren, S., & Korps, M. (2018). A Mechanism for Allocating Benefits and Costs from Transmission Interconnections under Cooperation: A Case Study of the North Sea Offshore Grid. *The Energy Journal*, *39*(01). https://doi.org/10.5547/01956574.39.6.mkri

Lavrijssen, S., & Carrillo Parra, A. (2017). Radical Prosumer Innovations in the Electricity Sector and the Impact on Prosumer Regulation. *Sustainability*, *9*(7), 1207. https://doi.org/10.3390/su9071207

Lehr, U., Lutz, C., & Edler, D. (2012). Green jobs? Economic impacts of renewable energy in Germany. *Energy Policy*, *47*, 358–364. https://doi.org/10.1016/j.enpol.2012.04.076

Lüth, A., Werner, Y., Egging-Bratseth, R., & Kazempour, J. (2022). *Electrolysis as a Flexibility Resource on Energy Islands: The Case of the North Sea* (Working Paper No. 13-2022). Copenhagen Business School. https://hdl.handle.net/10398/1973da63-75ba-4a5b-892d-984bd072dc79

Lüth, A., Zepter, J. M., Del Crespo Granado, P., & Egging, R. (2018). Local electricity market designs for peer-to-peer trading: The role of battery flexibility: The role of battery flexibility. *Applied Energy*, *229*, 1233–1243. https://doi.org/10.1016/j.apenergy.2018.08.004

Marten, A.-K., Akmatov, V., Sørensen, T. B., Stornowski, R., Westermann, D., & Brosinsky, C. (2018). Kriegers flak–combined grid solution: coordinated cross–border control of a meshed HVAC/HVDC offshore wind power grid. *IET Renewable Power Generation*, *12*(13), 1493–1499. https://doi.org/10.1049/iet-rpg.2017.0792

Martini, J. (2021). Eksperter dumper beregninger bag energiø. *JP/Politikens Hus A/S*. https://energiwatch.dk/Energinyt/Politik____Markeder/article12879183.ece

McDonagh, S., Ahmed, S., Desmond, C., & Murphy, J. D. (2020). Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment. *Applied Energy*, *265*, 114732. https://doi.org/10.1016/j.apenergy.2020.114732

Meeus, L. (2015). Offshore grids for renewables: do we need a particular regulatory framework? *Economics of Energy & Environmental Policy*, *4*(1), 85–96. https://doi.org/10.5547/2160-5890.4.1.lmee

Misyris, G., van Cutsem, T., Møller, J., Dijokas, M., Estragués, O. R., Bastin, B., Chatzivasileiadis, S., Nielsen, A., Weckesser, T., Østergaard, J., & Kryezi, F. (2020). *North Sea Wind Power Hub: System Configurations, Grid Implementation and Techno-economic Assessment*. https://arxiv.org/pdf/2006.05829

Morstyn, T., Farrell, N., Darby, S. J., & McCulloch, M. D. (2018). Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. *Nature Energy*, *3*(2), 94–101. https://doi.org/10.1038/s41560-017-0075-y

Munda, G. (2005). Multiple Criteria Decision Analysis and Sustainable Development. In F. S. Hillier, J. Figueira, S. Greco, & M. Ehrogott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys* (pp. 953–986). Springer New York. https://doi.org/10.1007/0-387-23081-5_23

Münster, M., Moller Sneum, D., Bramstoft, R., Buhler, F., Elmegaard, B., Giannelos, S., Strbac, G., Berger, M., Radu, D.-C., Elsaesser, D., Oudalov, A., & Iliceto, A. (2020). *Sector Coupling: Concepts, State-of-the-art and Perspectives*. https://orbi.uliege.be/handle/2268/244983

Newbery, D., Pollitt, M. G., Ritz, R. A., & Strielkowski, W. (2018). Market design for a high-renewables European electricity system. *Renewable and Sustainable Energy Reviews*, *91*, 695–707. https://doi.org/10.1016/j.rser.2018.04.025

North Sea Wind Power Hub. (2017). Wind Capacity Study Dogger Bank. https://northseawindpowerhub.eu/knowledge/wind-capacity-study-dogger-bank

North Sea Wind Power Hub. (2019). *Modular Hub-and-Spoke: Specific Solution Options*. https://northseawindpowerhub.eu/wp-content/uploads/2019/07/Concept_Paper_3-Specific-solution-options.pdf

North Sea Wind Power Hub. (2020). *Market setup options to integrate hybrid projects into the European electricity market*. https://northseawindpowerhub.eu/wp-content/uploads/2020/06/NSWPH-Discussion_Paper_Market-Setups-for-Hybrid-projects1.pdf

North Sea Wind Power Hub. (2021). Vision. https://northseawindpowerhub.eu/vision/

Oei, P.-Y., Hermann, H., Herpich, P., Holtemöller, O., Lünenbürger, B., & Schult, C. (2020). Coal phase-out in Germany – Implications and policies for affected regions. *Energy*, *196*, 117004. https://doi.org/10.1016/j.energy.2020.117004

Padmalal, D., & Maya, K. (2014). *Sand Mining*. Springer Netherlands. https://doi.org/10.1007/978-94-017-9144-1

Plechinger, M. (2021). Politisk flertal vedtager kunstig energiø i Nordsøen. *JP/Politikens Hus A/S*. https://watchmedier.dk/nyheder/politik/article12738449.ece

Pope, C. A., Dockery, D. W., & Schwartz, J. (1995). Review of Epidemiological Evidence of Health Effects of Particulate Air Pollution. *Inhalation Toxicology*, *7*(1), 1–18. https://doi.org/10.3109/08958379509014267

Puka, L., & Szulecki, K. (2014). The politics and economics of cross-border electricity infrastructure: A framework for analysis. *Energy Research & Social Science*, *4*, 124–134. https://doi.org/10.1016/j.erss.2014.10.003

Ramsebner, J., Haas, R., Ajanovic, A., & Wietschel, M. (2021). The sector coupling concept: A critical review. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(4), e396. https://doi.org/10.1002/wene.396

Schlachtberger, D. P., Brown, T., Schramm, S., & Greiner, M. (2017). The benefits of cooperation in a highly renewable European electricity network. *Energy*, *134*, 469–481. https://doi.org/10.1016/j.energy.2017.06.004

Scholten, D., Bazilian, M., Overland, I., & Westphal, K. (2020). The geopolitics of renewables: New board, new game. *Energy Policy*, *138*, 111059. https://doi.org/10.1016/j.enpol.2019.111059

Singlitico, A., Campion, N. J. B., Münster, M., Koivisto, M. J., Cutululis, N. A., Suo, C. J., Karlsson, K., Jørgensen, T., Waagstein, J. E., & Bendtsen, M. F. (2020). Optimal placement of P2X facility in conjunction with Bornholm energy island: Preliminary overview for an immediate decarbonisation of maritime transport. https://orbit.dtu.dk/en/publications/optimal-placement-of-p2x-facility-in-conjunction-with-bornholm-en

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition*, *1*, 100005. https://doi.org/10.1016/j.rset.2021.100005

Snyder, B., & Kaiser, M. J. (2009). Ecological and economic cost-benefit analysis of offshore wind energy. *Renewable Energy*, *34*(6), 1567–1578. https://doi.org/10.1016/j.renene.2008.11.015

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the direct rebound effect: A review. *Energy Policy*, *37*(4), 1356–1371. https://doi.org/10.1016/j.enpol.2008.11.026

Soukissian, T., Denaxa, D., Karathanasi, F., Prospathopoulos, A., Sarantakos, K., Iona, A., Georgantas, K., & Mavrakos, S. (2017). Marine Renewable Energy in the Mediterranean Sea: Status and Perspectives. *Energies*, *10*(10), 1512. https://doi.org/10.3390/en10101512

Spiecker, S., Vogel, P., & Weber, C. (2013). Evaluating interconnector investments in the north European electricity system considering fluctuating wind power penetration. *Energy Economics*, *37*, 114–127. https://doi.org/10.1016/j.eneco.2013.01.012

Strbac, G., Moreno Vieyra, R., Konstantelos, I., Aunedi, M., & Pudjianto, D. (2014). *Strategic Development of North Sea Grid Infrastructure to Facilitate Least-Cost Decarbonisation.* Imperial College London. https://doi.org/10.25561/28452

Sun, X., Huang, D., & Wu, G. (2012). The current state of offshore wind energy technology development. *Energy*, *41*(1), 298–312. https://doi.org/10.1016/j.energy.2012.02.054

Sunila, K., Bergaentzlé, C., Martin, B., & Ekroos, A. (2019). A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis. *Energy Policy*, *128*, 775–782. https://doi.org/10.1016/j.enpol.2019.01.047

Tobiasson, W., & Jamasb, T. (2016). The Solution that Might Have Been: Resolving Social Conflict in Deliberations about Future Electricity Grid Development. *Energy Research & Social Science*, *17*, 94–101. https://doi.org/10.1016/j.erss.2016.04.018

Tosatto, A., Beseler, X. M., Østergaard, J., Pinson, P., & Chatzivasileiadis, S. (2021). *North Sea Energy Islands: Impact on National Markets and Grids*. https://arxiv.org/pdf/2103.17056

Traber, T., Koduvere, H., & Koivisto, M. (2017). Impacts of offshore grid developments in the North Sea region on market values by 2050: How will offshore wind farms and transmission lines pay? *2017 14th International Conference on the European Energy Market (EEM)*, 1–6. https://doi.org/10.1109/EEM.2017.7981945

UNEP & IEA. (2019). *2019 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector* (No. 978-92-807-3768-4). United Nations Environment Programme and International Energy Agency. https://wedocs.unep.org/handle/20.500.11822/30950?show=full

Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews*, *122*, 109547. https://doi.org/10.1016/j.rser.2019.109547

van der Meijden, M. (2016). Future north sea infrastructure based on dogger bank modular island. In U. Betancourt & T. Ackermann (Eds.), *15th Wind Integration Workshop*. Energynautics GmbH.

Vrana, T. K., & Torres Olguin, R. E. (2015). *Technology perspectives of the North Sea Offshore and storage Network (NSON)* (No. 978-82-594-3628-3). https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2400329

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021

Wei, M., Patadia, S., & Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, *38*(2), 919–931. https://doi.org/10.1016/j.enpol.2009.10.044

Weichenhain, U., Elsen, S., Zorn, T., & Kern, S. (2019). *Hybrid projects: How to reduce costs and space of offshore developments: North Seas Offshore Energy Clusters study*. Publications Office of the European Union. https://doi.org/10.2833/416539

Wilkens, I. (2012). *Multikriterielle Analyse zur Nachhaltigkeitsbewertung von Energiesystemen - Von der Theorie zur praktischen Anwendung* (Dissertation). Technische Universität Berlin. https://doi.org/10.14279/depositonce-3385

Xiong, B., Predel, J., Del Crespo Granado, P., & Egging-Bratseth, R. (2021). Spatial flexibility in redispatch: Supporting low carbon energy systems with Power-to-Gas. *Applied Energy*, *283*, 116201. https://doi.org/10.1016/j.apenergy.2020.116201

Zhang, H., Tomasgard, A., Knudsen, B. R., Svendsen, H. G., Bakker, S. J., & Grossmann, I. E. (2022). Modelling and analysis of offshore energy hubs. *Energy*, *261*, 125219. https://doi.org/10.1016/j.energy.2022.125219

Zheng, Y., You, S., Bindner, H. W., & Münster, M. (2022a). Incorporating optimal operation strategies into investment planning for wind/electrolyser system. *CSEE Journal of Power and Energy Systems*. https://doi.org/10.17775/CSEEJPES.2021.04240

Zheng, Y., You, S., Bindner, H. W., & Münster, M. (2022b). Optimal day-ahead dispatch of an alkaline electrolyser system concerning thermal–electric properties and state-transitional dynamics. *Applied Energy*, *307*, 118091. https://doi.org/10.1016/j.apenergy.2021.118091

Paper B

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How to Connect Energy Islands?

Trade-Offs between Hydrogen and Electricity Infrastructure

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CHAPTER B

How to Connect Energy Islands?

B.1 Introduction

Offshore wind energy in Europe is developing fast, and plans to build large capacities in the available waters are evolving rapidly; see for example the recent Esbjerg and Marienborg declarations of the littoral states of the North and Baltic Seas. Anticipated cost reductions in the technology and avoiding not-in-my-back-yard issues create a major opportunity for supporting the decarbonisation efforts in Europe. Together with solar photovoltaics (PV) generation, large-scale offshore wind energy has been declared to fill the power supply gap that the shutdown of nuclear and fossil fuel plants will leave behind (Victoria et al., 2020). Some countries have made considerable progress over the last decade. For example, the German electricity system saw a wind share of 24.4%, and a total intermittent renewable energy sources (RES) share of 32.9% in 2020 (Bundesnetzagentur, 2021). The integration of these significant RES shares has been relatively easy to manage, refuting older predictions of disruptions in the reliability of the power system due to increasing shares of fluctuating sources (Castillo & Gayme, 2014). However, this integration still causes higher costs and curtailment (Joos & Staffell, 2018) that are undesirable and hinder the decarbonisation of the energy system.

Among the solutions are the provision of flexibility by grid extensions, storage technologies, and sector coupling (Gerbaulet & Lorenz, 2017; Pilpola & Lund, 2019). With the publication of the hydrogen strategy, there are major plans in the European Union (EU) to create a hydrogen economy and develop the necessary conversion capacities, including the extension of power-to-gas (PtG) via electrolysis. PtG can serve both purposes: providing flexibility to the electricity system and producing hydrogen to meet demand from other sectors like industry and transportation. When wind farms are moved offshore, production will be affected by fluctuations at sea. To balance those, electrolysis can also be moved close to the generation to so-called *energy islands*.

Energy islands are a European-born idea. The term is typically used for projects in the waters of Denmark and the UK, e.g., the North Sea Wind Power Hub or VindØ. The design of these islands is currently under development, but Figure B.1 shows early ideas for energy islands that host conversion equipment for sector coupling, such as electrolysers. Energy islands are expected to be valuable for providing demand-side flexibility with electrolysis to reduce curtailment, lower stress on the electricity grid, and produce hydrogen offshore for industry. In addition, they can serve as inter-country electricity connections, which are beneficial for balancing electricity flows (Schlachtberger et al., 2017).

Besides the electricity- and hydrogen-focused projects in Denmark (VindØ and Bornholm) and the North Sea Wind Power Hub, AquaVentus has gathered more than 90 partners to develop a related family of projects around the German Island of Heligoland. Here, 10 GW of offshore wind capacity will be developed by 2035 for the offshore production of hydrogen, including the necessary transportation infrastructure. In this case, though, no electricity connection to shore is currently envisaged.

With this paper, we contribute to the discussion of how to design and plan offshore energy infrastructure, specifically around energy islands, and analyse the trade-offs between offshore electricity and hydrogen infrastructure. Our guiding research question asks how energy islands can be integrated with onshore energy systems and what the system implications of such an integration would be. With the help of an integrated

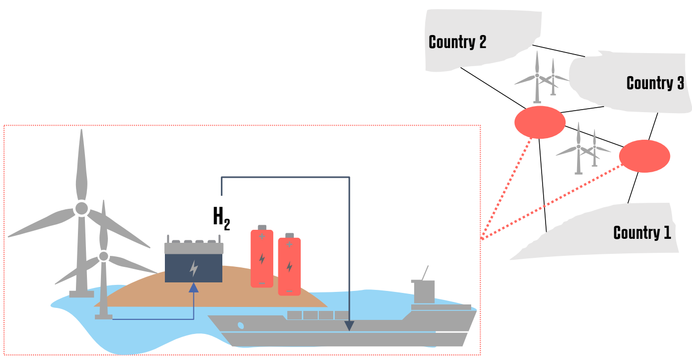


Figure B.1. An abstract sketch of an energy island following first visions presented in COWI (2021).

capacity expansion and electricity dispatch model, including a detailed grid representation, we identify economically viable investment options in cables to and between energy islands, and in electrolysers offshore and onshore. We find that the role of offshore electrolysis is to limit investments in expensive long-distance cables between distant offshore wind sites and the mainland. The current cost of electrolyser technology makes it worth using existing nuclear power for hydrogen production if this is not restricted. We find that investments are sensitive to future hydrogen prices but less so to an increase in CO_2 prices. Using network data for 2030 without further expansion possibilities influences the electricity and hydrogen infrastructures built in the model, and exogenously increasing onshore network capacity leads to lower system costs due to lower curtailment and more direct consumption of electricity leading to less hydrogen production and electrolyser capacity.

The remainder of this paper is structured as follows: Section B.2 presents related literature on offshore energy systems, system modelling, and electrolysis. In Section B.3 we describe the model framework, data sources, data handling, and the case study. The results, a discussion of them, and a sensitivity analysis are given in Section B.4, and we summarise the main findings and provide an outlook on future research in Section B.5.

B.2 Literature and Background

Energy islands are seen to establish offshore in centres of large-scale wind power production. The literature on this topic is not extensive yet but builds on the idea of setting up ”power link” islands in a meshed offshore grid (Kristiansen et al., 2018). Meshed offshore grids describe the connection of countries via offshore wind farms and interconnecting offshore wind farms among themselves (Dedecca et al., 2019). Early research on meshed offshore grids has developed model frameworks to analyse the impact of offshore grids (Trötscher & Korpås, 2011) and allow project consortia such as Kriegers Flak[1] to examine the impact of interconnected wind farms. Connecting wind farms and countries at the same time also

[1]See Kriegers Flak: en.energinet.dk/Infrastructure-Projects/Projektliste/KriegersFlakCGS.

takes market integration one step further. Traditionally, wind farms are connected only to the country they were built in, or there are radial connections between two countries that act as interconnectors. In a meshed grid, those two traditional structures converge towards interlinked systems (Gorenstein Dedecca et al., 2017). Interconnection has been called a pillar of renewable energy systems and leads to greater utilisation of renewable resources (Schlachtberger et al., 2017). Market integration will influence welfare and price development in the connected countries. Early studies agree that offshore grids increase welfare (Egerer et al., 2013; Strbac et al., 2014). The benefits, however, are allocated asymmetrically among the connected countries: suppliers in high-price areas and consumers in low-price areas will see some negative impacts (Egerer et al., 2013). The idea of energy islands was developed by industrial consortia around 2016 and has a lot of characteristics in common with offshore grids and interconnections. Like offshore grids, energy islands will affect market prices and welfare.

Tosatto et al. (2022) build on the welfare analysis and investigate the impacts of a North Sea energy island on the European electricity system. In a setting without sector coupling and with electricity production only, their results show that overall welfare will increase but the distribution of benefits will be asymmetric: consumer welfare will increase while producers' welfare in exporting countries will be adversely affected, which is well in line with the findings for offshore grids. Zhang et al. (2022) model offshore wind hubs in the North Sea to decarbonise the Norwegian continental shelf. Establishing a cost-minimising, mixed-integer linear investment planning and operations model, they develop scenarios for investment into renewable generation, storage, electricity transmission, and offshore hubs with hydrogen conversion equipment under specific CO_2 prices and argue that offshore wind and a cable connection to shore can halve current emissions in a scenario of moderate CO_2 prices.

Singlitico et al. (2021) were the first to analyse the combination of electricity and hydrogen production from offshore wind plants on large energy islands. In a pre-defined setting of cable connection and electrolyser size, the authors tested different operating modes in which conversion to hydrogen or transport via electrical infrastructure was prioritised. They find that offshore placement can be advantageous, and that a hydrogen-powered operating mode can reduce the levelised cost of hydrogen to the point that it competes with hydrogen from fossil fuels. Gea Bermúdez et al. (2021) find in a capacity expansion model (CExM) that forcing hydrogen offshore will lead to higher system costs and onshore hydrogen production is more likely to be cost-efficient due to patterns following PV generation. Their analysis is based on a zonal market representation with cross-border flows. This approach is likely to underestimate inner-zonal congestion which could lead to an overestimation of electricity flows across zones.

Although analyses of offshore grids, which form the infrastructure for energy islands, are more mature, the role, sizing, and siting of electrolysers have not been explored extensively. In combination with multi-country cable connections, new options for linkages with existing energy systems are opening up. Jansen et al. (2022) analyse the role of the *North Sea Wind Power Hub*, an energy island in the North Sea, and iteratively assess the roles of connections by cable and hydrogen pipelines under certain assumptions. In a bottom-up cost assessment, they find that large connected wind generation capacities can make an energy island profitable. But their analysis is based on exogenous capacity assumptions about wind farm and electrolyser sizes. Our study makes use of an integrated capacity expansion and dispatch model to endogenise the decision whether to connect energy islands by cable or pipeline and at what capacity.

B.3 Model and Setup

We develop an integrated capacity expansion and electricity dispatch model with high spatial and temporal resolution and including physical constraints on the power network. The model is set up as a cost minimisation problem and allows for investments in hydrogen production or in cables to connect offshore energy production hubs with either onshore electricity systems or other offshore wind farms. Hydrogen is sold at an exogenously fixed price. This model was inspired by the techno-economic model ELMOD (Leuthold et al., 2008) and the cost minimisation approach of a later version of dynELMOD (Gerbaulet & Lorenz, 2017). The investment model is based on LIMES-EU by Nahmmacher et al. (2014) and Alharbi and Bhattacharya (2014). To limit the solution space, exogenous scaling of RES, demand, and conventional generation for a multi-year representation is applied as in Weibezahn et al. (2020). The time series reduction and scaling are based on Göke and Kendziorski (2022) and Poncelet et al. (2017).

min day-ahead generation costs
+ cost for electrolysis infrastructure
+ cost for electricity connections
- profits from hydrogen sales

s.t. nodal power balance
generator capacity limits
storage limits
electrolyser production limits
network constraints (DC load flow)

Figure B.2. Schematic overview of our model. The mathematical equations are found in Appendix B.5.

Figure B.2 presents the structure of the model. The objective is to minimise the costs of electricity dispatch and endogenously determined capacity expansions in electrolysers and DC power connections to the proposed energy islands. In the dispatch, we include short-run marginal costs for thermal power plants, cost of curtailing load, and a discharge penalty for storage. In addition, we subtract income from hydrogen production. RES do not incur marginal costs. Investments in electrolysers and connecting power lines are allowed at specific costs. For electrolysers, we include annual operation and maintenance costs. We limit the model by a set of operational constraints, including capacity limits for generators, electrolysers, and storage, and network constraints including a power flow approximation. See Appendix B.5 for a full description of the model equations.

The main endogenous decisions of the model are the dispatch, the produced quantity of hydrogen, the capacity investments in electrolysers, and the cable infrastructure around energy islands and offshore wind parks. The decisions are based on and matched to the exogenous parameters. For this model, the grid characteristics of an existing power grid and the generation capacities, profiles, and cost parameters are the limiting factors.

This capacity expansion model can be applied to any setup with a combined investment decision into hydrogen and electricity infrastructure. In the following, we apply it to analyse the plans for energy islands in the North and Baltic Seas. We run the model for the years 2030, 2035, and 2040 allowing for investments in each time step.

B.3.1 Energy Islands in Northern Europe

The islands are expected to be built close to the Danish island of Bornholm in the Baltic Sea, off the eastern coast of Denmark, on the Dogger Bank in the North Sea, and off the western coast of Denmark. Each project is expected to be slightly different in wind park size, interconnection, and technology placed on the island. The first estimates for connections and technologies have been presented by project stakeholders and the Danish government (COWI, 2021). With this in mind, we analyse the trade-off between interconnecting power lines and electrolysis on the energy island. We add the North Sea energy islands as done by Tosatto et al. (2022) and the Bornholm Energy Island in accordance with the latest project proposal (COWI, 2021). In Table B.1, we list the projected wind park capacities at the three energy islands, the countries they can connect to, and the abbreviation we use for them (NSEI1, NSEI2, BHEI). We locate the islands following the first feasibility studies by COWI (2021) and the North Sea Wind Power Hub Consortium. The Danish Energy Agency designated specific areas[2] in Danish waters for the projects and we use the centre of each area as our location for the hub.

B.3.2 Data

The model is set up as an integrated capacity expansion and dispatch model, which needs technical data on the electricity system, and information on production and investment expenditures. This section describes the data collection and processing for our case study. We structure it into a part on creating a grid representation with generation units of different energy carriers (Subsection B.3.2.1), a summary of scaling paths (Subsection B.3.2.2) for the future system, and an overview of the financial input

[2]See Danish Energy Agency (2022): ens.dk/en/our-responsibilities/wind-power/energy-islands.

data (Subsection B.3.2.3). Because the problem exceeds current computational capabilities, we reduce the time series and describe the assumptions behind our method in Subsection B.3.2.4.

B.3.2.1 Data Set

We start our data set generation by collecting a base data set for 2030. The grid and locations of conventional power generation units published by Hörsch, Hofmann, et al. (2018) serve as a basis. This data set includes a 1024-node representation of the European power grid with load and conventional power plant capacities matched to all included nodes. We extend the available grid with new infrastructure projects from the Ten-Year Network Development Plan (TYNDP) 2020 project list[3] and include the energy islands as shown in Table B.1. Figure B.6 in the Appendix shows the resulting grid. Planned offshore wind power projects[4] and their capacities are clustered in 19 groups along the coasts of the North and Baltic Seas. Each cluster can connect to the existing onshore grid. The capacity expansion part of the model endogenously determines sizes and points of connection.

Wind and PV generation potential at a nodal level are also taken from Hörsch, Hofmann, et al. (2018). We normalise the potentials with the currently installed capacities available from ENTSO-E[5] This way, we maintain the ratio of geographical distribution and ensure the correct sum at a bidding zone level. We use the high resolution of the Open Power System Data by Schlecht and Simic (2020) in Germany, Denmark, and the UK to replace the generation assets listed in Hörsch, Hofmann, et al. (2018). Together with the normalised potentials, we aggregate and match each to the closest node of the respective bidding zone.

The aggregated renewable energy generators obtain time series based on their locations and types from renewables.ninja (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016), with hourly resolution. To translate wind speed into the power output of a generator, we use the power curve of a Vestas V80 2000 generator with a hub height of 100 meters. For PV, we assume a 45° tilt angle and strict south-facingness.

[3] See TYNDP 2020 Project List: tyndp2020-project-platform.azurewebsites.net.
[4] 4C Offshore - Global Offshore Map (2022): map.4coffshore.com.
[5] See ENTSO-E (2022): transparency.entsoe.eu.

Table B.1. Summary of important input data. The upper part describes the parameters used in the model. The lower part lists the relevant characteristics of each energy island.

Parameter	Description	Unit	Value
c^{D}	penalty for lost load	€/MWh	3,000
c^{E}		€/MW	offshore: 645,000 onshore: 450,000
c^{L}	cost for line expansion	€/(MW·km)	1,950
c_e^{O}	cost for electrolyser operation	% of CAPEX	2
c^{S}	cost for storage depletion	€/MWh	0.1
p^{CO_2}	carbon price	€/t	80, 120, 160
q	discount factor		1.04
r	interest rate	%	4
r_e^{H}	hydrogen sales price	€/MWh	108
t	model years		2030, 2035, 2040
η^{H}	electrolyser efficiency		0.75
η^{S}	storage efficiency		0.8
v	transmission reliability margin		0.7
countries	BE, CZ, DE, DK, FI, NL, NO, PL, SE, UK		
reference year	2018		

Island	Model name	Connections	Wind park size
NSWPH	NSEI1	NO, DE, DK, NL	10 GW
Danish EI	NSEI2	BE, DE, DK, NL, UK	10 GW
Bornholm	BHEI	DE, DK, PL, SE	3 GW

Hydropower plants in our data set are based on the open-source database by the European Commission, Joint Research Centre (JRC) (2019). The hydropower plants are matched to the nearest node in the grid. We distinguish run-of-river, reservoir, and pumped hydro. Run-of-river hydro is treated as a renewable resource with zero marginal cost, and its production potential is based on a time series from EMPIRE[6] (Backe et al., 2022). Reservoirs are dispatchable resources with an upper electricity production limit within the chosen time horizon, which is based on historical production data available on ENTSO-E's Transparency Platform[5]. We estimate the round-trip efficiency of pumped hydro to be 80% (Hameer & van Niekerk, 2015). Data on load, renewable energy production, and hydropower follows patterns from the historical time series of the year

[6]openEMPIRE is available on GitHub: github.com/ntnuiotenergy/OpenEMPIRE.

2018 and is scaled to match the expected sum of future years.

B.3.2.2 Scaling Paths

Starting with the base data set that we compiled from the sources listed above, we expect demand profiles, generation from renewable energy sources, and installed conventional generation capacity to change over the modelled time horizon from 2030 to 2040. We use scaling factors to adjust current capacities to future projections, using data from the TYNDP 2020[7] and work with the Gradual Development scenario. For each generation technology and year, the TYNDP 2020 value divided by the current bidding zone value determines a scaling factor and is used to match the projections for future years. Demand scaling follows the same principle. This scaling preserves the geographical distribution of load and demand within the bidding zones. When new technologies are introduced, the projected capacity is distributed equally over all the nodes in the bidding zone. In some cases, the offshore wind clusters we added from the list of planned projects exceed the projections of the TYNDP. In those cases, the offshore clusters remain in our data set as they are planned, and we reduce capacities at other offshore nodes in the bidding zone to match the overall projections for the zone.

B.3.2.3 Financial Parameters

Prices and costs are the main driving factors in the model. We use fuel prices provided in the PyPSA data set (Hörsch, Hofmann, et al., 2018) to calculate production costs for each generation technology. Table B.1 summarises the techno-economic parameters used in the model. Below, we explain the origin of the data and some additional assumptions.

RES are assumed to incur no marginal costs. At the end of 2021, fuel prices reached record highs, but this did not change the merit order of power plant use. Recent price peaks resulting from the Russian invasion of Ukraine have not been incorporated in any scenario in this study.

In our model, we assume that capital investments are financed by annuity loans over the lifetime of the assets. The interest rate is fixed at

[7]Ten Year Network Development Plan 2020,European Network of Transmission System Operators for Electricity (2020).

4%. The model calculates every five years from 2030 to 2045, and payments are discounted to the reference year 2030. The connection cables are planned as DC connections. This is done for most big offshore wind parks in the North Sea, with the advantage of coupling non-synchronous countries, for example Sweden with Germany or Poland. The integration of a DC cable requires converter stations on both sides. We use costs of €1950/(MW·km) for our connections (Lauria et al., 2016). Discharging storage induces a small cost of €0.1/MW to prevent simultaneous charging and discharging by the model.

We use alkaline electrolysers, and we differentiate between onshore and offshore installation. Onshore electrolysers have capital costs of €450/kW, and 2% of capital costs occur as annual operational expenditure (Danish Energy Agency, 2022). Offshore electrolysers are more expensive because of transport, marine conditioning, pipeline construction, and additional operating costs and sum to €645/kW. The efficiency of offshore and onshore technology is set to 75% and the lifetime is estimated to be 30 years (Danish Energy Agency, 2022). For hydrogen, we use the lower heating value of 33.33 kWh/kg.

We keep the expenditures for electrolyser capacity investments fixed at the 2030 predictions. We are aware that our model's hydrogen investment results depend heavily on the imposed price development paths and power flow changes in the power system.

In the objective function, hydrogen sales act as income to incentivise investments in electrolysers. The price predictions for carbon emission-free hydrogen, also referred to as ”green hydrogen”[8], have a wide range. An overview of the results of scientific publications can be found in the Appendix, in Table B.8. We set the price for our analysis to €3.25/kg (equivalent to just above €100/MWh) as in Glenk and Reichelstein (2019).

B.3.2.4 Time Series Reduction

Capacity expansion models can become quite complex as detail is added. Some models apply methods to reduce time series and determine a representative period to reflect the full time horizon (Hoffmann et al., 2020).

[8]Hydrogen is in fact a colourless gas and all hydrogen is a gas with identical chemical characteristics independent of the method of generation.

The choice of reduction technique influences the outcome and affects computational complexity and implementation efforts (Göke & Kendziorski, 2022; Kotzur et al., 2018; Poncelet et al., 2017; Schütz et al., 2018).

Especially when estimating the demand for storage in high-RES scenarios, time-series reduction methods must preserve fluctuations in generation, both long and short term, to obtain optimal capacities. To test existing principles, Göke and Kendziorski (2022) analyse different reduction methods for their adequacy for a capacity expansion model. Due to the absence of additional variables for the optimisation problem, they find speed advantages of chronological-sequence algorithms over grouped-period algorithms.

On the basis of these findings, we use the method of Poncelet et al. (2017), which bases the time series selection on an optimisation problem. The algorithm compares the approximated and original duration curves and minimises the difference in equal sized sections called bins. Both curves' load spans are segmented into a finite number of intervals, and all the deviations form an error term that is minimised in a mixed-integer problem for all examined RES curves.

We use 20 bins and chronological sequencing with re-scaling without changing the length of the periods to shorten the year to 21 representative days. The time series reduction method of Poncelet et al. (2017) is computationally costly, especially on our data set, with simultaneous optimisation of 544 nodes with RES infeed. For capacity expansion models of energy systems, the objective values of the model run with shortened time series deviate only slightly from the full time series objectives, according to Zatti et al. (2019). We can confirm this with the results of running over longer and reduced periods.

B.3.3 Case Setup

We set up four different cases and compare their results. Table B.2 provides an overview of the cases. The first is a reference case, *BAU*, in which all wind farms are placed in accordance with current proposals (see Table B.1) and we only determine cable connections to the surrounding countries. To analyse the trade-offs between electrolysers and cable expansions, we add options for electrolysis (as opposed to cable investment only) in three further cases. In the second case, *OFFSH*, we allow investment in offshore electrolysers on the energy islands. In case three, *COMBI*, we allow additional investment in onshore electrolysis at the landing points—the points of connection between the onshore and offshore networks. In case four, *STAKE*, we limit the cable expansions to shore for each island to the maximum capacity planned by the stakeholders.

Table B.2. Overview of cases defined for the analysis, including abbreviations.

Case	**Name**	**Investable line capacity**	**Investable electrolyser capacity**
reference	BAU	unlimited	none
offshore H_2	OFFSH	unlimited	unlimited offshore only
offshore & onshore H_2	COMBI	unlimited	unlimited
stakeholder	STAKE	≤ 10 GW for both NSEI1-2, ≤ 3 GW for BHEI	unlimited

B.4 Results and Discussion

In this section, we describe the results of the case study, analysing energy hubs in the North and Baltic Seas. In the first part, we describe the overall results and identify the main findings. In Section B.4.2, we focus on offshore electrolysers and why they are being built. In Section B.4.3, we present sensitivity studies to test the impact of the assumptions made about carbon and hydrogen prices and the electricity grid.

B.4.1 Main Findings

This section presents the main results for the four cases and describes Table B.2. We start by looking at overall system costs and then discuss cable expansion and electrolyser investments for each case separately.

The combined investment and dispatch costs scaled up to annual costs differ among the cases. *COMBI* is the cheapest at €112 billion. *STAKE* has about the same cost. The most expensive is *BAU* at €140 billion (25% higher than COMBI). *OFFSH* is the second most expensive, with costs about 1.8% higher than *COMBI.* This suggests that sales from hydrogen production can visibly lower system costs, despite the significant investment expenditures that must be paid off. Offshore cable capacity

Table B.3. Case study results: % changes relative to the case with more restrictions in the lines above.

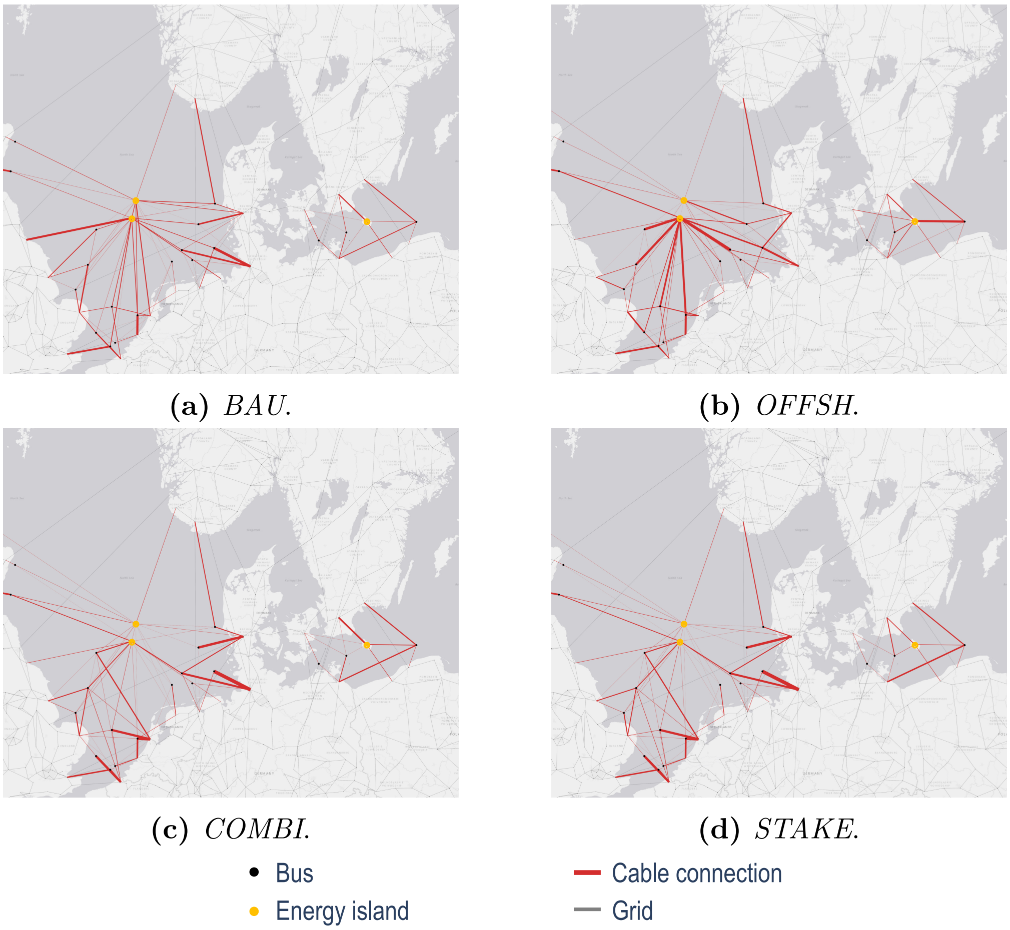
	Electrolyser capacity [GW]			**Hydrogen production [TWh]**			**Curtailment [TWh]**			**Conventional generation [TWh]**		
	2030	**2035**	**2040**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**
BAU												
offshore	–	–	–	–	–	–	6.8	6.4	6.7	–	–	–
onshore	–	–	–	–	–	–	67.5	75.9	87.9	437.1	430.6	473.6
OFFSH												
offshore	49.8	54.6	60.9	215.8	222.7	251.0	1.8	1.3	1.3	–	–	–
rel. change to BAU	–	–	–	–	–	–	-73.8%	-79.2%	-80.5%	–	–	–
onshore	–	–	–	–	–	–	8	13.3	20.1	471.6	448.5	492.6
rel. change to BAU	–	–	–	–	–	–	-88.2%	-82.5%	-77.1%	7.9%	4.2%	4.0%
COMBI												
offshore	21.5	21.5	21.5	97.0	94.5	97.4	1.6	1.3	1.2	–	–	–
rel. change to OFFSH	-57.0%	-60.7%	-64.8%	-55.0%	-57.6%	-61.2%	-7.8%	0.7%	-8.7%	–	–	–
onshore	34.6	39.6	47.3	126.9	137.8	165.2	7.3	12.3	18.5	474.9	452.1	496.2
rel. change to OFFSH	–	–	–	–	–	–	-8.9%	-7.6%	-8.2%	0.7%	0.8%	0.7%
STAKE												
offshore	22.6	22.6	22.6	99.1	95.2	102.4	1.6	1.3	1.2	–	–	–
rel. change to COMBI	5.3%	5.3%	5.3%	2.1%	0.7%	5.1%	0.3%	-1.6%	-1.0%	–	–	–
onshore	33.5	38.4	46.2	125.0	137.2	160.3	7.3	12.3	18.5	475.1	452.2	496.3
rel. change to COMBI	-3.1%	-2.9%	-2.4%	-1.5%	-0.4%	-3.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%

is built in all cases, and whenever it is allowed, significant electrolyser capacities are placed either onshore or offshore to produce and sell hydrogen. The positioning of electrolysis on the energy islands influences the cable allocation. Table B.3 summarises the results of all four cases and the relative changes between successive cases. [9] Together with Figures B.3 and B.4 and Table B.4, it serves as the basis for the following analysis. Figure B.3 pictures the cable capacities, Figure B.4 maps electrolyser size and location, and Table B.4 summarises the data on offshore grids.

B.4.1.1 Reference Case: BAU

In *BAU*, an aggregated 17.5 GW of cable connections are built in 2030 to connect the energy islands to shore (Table B.4). All countries are connected from the first period. Over the years, aggregate capacity increases very modestly to 18.0 GW in 2035 and 18.2 GW in 2040. In addition to direct cables, a strong offshore grid develops between the wind farm clusters, the islands, and the shores; see Figure B.3(a).

[9] Since cases two and three step-wise allow more investment compared to case one, and the fourth case provides a reality check for the third, we believe that these comparisons provide the most insight.

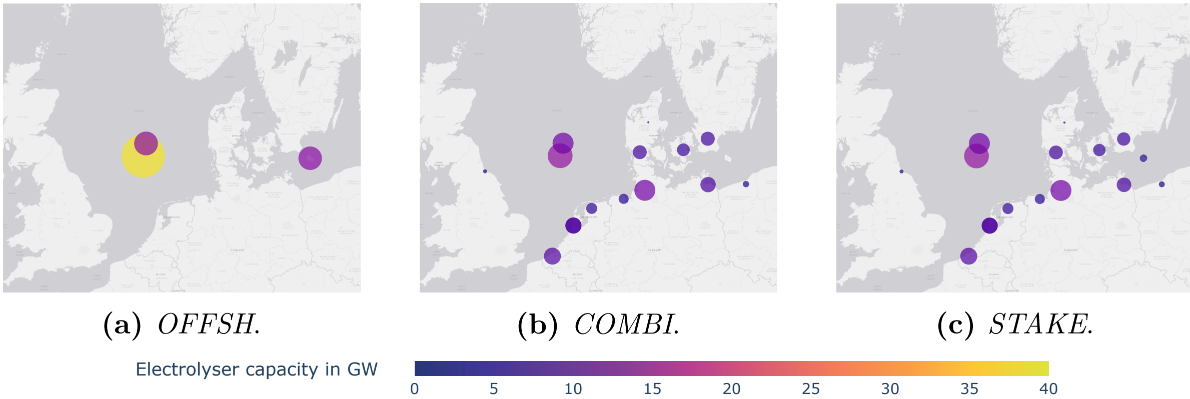


(a) *BAU.* **(b)** *OFFSH.* **(c)** *COMBI.* **(d)** *STAKE.*

Figure B.3. Comparison of cable connection capacity between the energy islands and shore in the different cases in 2040. The thickness of the red lines indicates the capacity of the constructed connection.

B.4.1.2 Offshore Electrolysis Only: OFFSH

Allowing electrolysis on the energy islands only results in lower direct power cable capacities to shore. In Table B.4, we see capacities of 5.1 GW in 2030 (70 % lower than BAU in the same year), 6.8 GW in 2035 and 9.7 GW in 2040 to connect the islands. The aggregate offshore electrolyser capacity is 49 GW in 2030 and increases evenly in every period to 60.9 GW in 2040. Most of the electrolyser capacity is built in the North Sea, specifically at NSEI1 (our reference to the North Sea Wind Power Hub), which is well-positioned between many countries and closer to their shores than NSEI2. Figure B.4(a) maps the electrolyser capacities in 2040 for the different cases to the locations. Comparing Figures B.3(a) and B.3(b), we see that NSEI1 not only develops more electrolyser capacity but is also better connected to shore than NSEI2. Although all direct connections from the islands to shore aggregate to no more than 10 GW, Figure B.3(b) also shows that connections from the offshore wind clusters to the islands are important. Allowing offshore electrolysis lowers the need for power cable capacity of the energy islands and the wind clusters to shore but leads to higher offshore cable connections between wind clusters and the energy islands. The aggregated capacity of electricity cables connecting offshore wind clusters and energy islands adds up to 46.8 GW in 2030, 52.1 GW in 2035, and 58.8 GW in 2040. Specifically, the wind farms off the coast of the Netherlands are connected by large cables to the energy islands.



(a) *OFFSH.* **(b)** *COMBI.* **(c)** *STAKE.*

Figure B.4. Comparison of electrolyser locations and capacities in the different cases in 2040.

Hydrogen production from the offshore electrolysers in 2040 adds up to 215 TWh, which is in line with the European industrial demand predicted by Agora Energiewende and AFRY Management Consulting (2021). In 2030, about half of the hydrogen production originates in avoided RES curtailment. However, electricity production from nuclear and biomass[10] is higher than in *BAU* (see Table B.10 in the Appendix), which is connected to the electricity-based hydrogen production. This suggests that existing nuclear capacities can generate at costs that are competitive for electrolysis.

[10]The model does not consider alternative use of biomass, e.g., direct gasification, but it only assumes direct power generation.

Table B.4. Capacity of cable connections at sea for each case and year.

	Energy island to shore [GW]			Wind cluster to island [GW]			Wind cluster to shore [GW]		
	2030	**2035**	**2040**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**
BAU	17.5	18.0	18.2	19.6	20.9	21.4	71.8	73.6	74.9
OFFSH	5.1	6.8	9.7	46.8	52.1	58.8	68.0	71.5	72.9
COMBI	7.7	8.7	9.4	11.7	14.2	16.8	98.6	103.3	106.3
STAKE	5.0	5.9	6.5	10.7	13.2	16.7	99.6	104.4	107.7

B.4.1.3 Combined Onshore and Offshore Electrolysis: COMBI

The option to invest in onshore electrolysis is represented in our *COMBI* case. In comparison to *OFFSH*, the aggregated capacity of cables directly connecting energy islands to shores are slightly higher; see Table B.4. However, they are much below *BAU* (about 55% lower in 2030, and comparably lower in 2035 and 2040). In COMBI, a meshed offshore grid or strong connections between the energy islands and the offshore wind clusters are not a significant part of the optimal system solution. In Figure B.3(c), we see that the offshore wind clusters are mostly connected to shore, meaning that landing points receive larger cables compared to *OFFSH*. Electrolysers in this case are mainly built onshore. Offshore electrolysers have 57% lower aggregate capacity and reach an aggregate size of 21.5 GW, split unevenly among the three islands. This entire offshore capacity is invested in the first period, and all is located in the North Sea on NSEI1 and NSEI2. Aggregate onshore electrolysis is greater than aggregate offshore capacity in *OFFSH*. In addition to offshore electrolysers, 34.6 GW of onshore electrolyser capacity is invested in by 2030 in *COMBI*. The aggregate capacity increases to 39.6 GW in 2035 and 47.3 GW in 2040, which is about a 10% increase per period. Aggregate hydrogen production is slightly higher in *COMBI* than in *OFFSH* due to the generally higher capacity of electrolysers. Onshore electrolysers are built at all landing points; the ones in the UK and Poland have the smallest capacities; see Figure B.4(b). The locations and development of electrolysers over the years follow RES expansion projects in the countries. Curtailment and conventional generation are at similar levels to *OFFSH*. Also here hydrogen is produced from electricity generated from nuclear and biomass (see Table B.10) that is not needed to satisfy electricity demand, similar to *BAU*.

B.4.1.4 Restricting Cable Connections: STAKE

In our last case, we consider current plans for cable capacities to connect the islands. In *STAKE*, cable expansion capacity is restricted to currently planned capacities: 1 GW of cable per GW of wind farm commissioned (c.f., COWI, 2021). This restriction does not change the results much and is comparable to the *COMBI* case with respect to both electrolyser and cable capacity; see Figures B.8 and B.9 in the Appendix.

B.4.1.5 Comparison of Cases

BAU leads to the highest need for cable investment in direct shore-island connections. Only allowing electrolyser capacity offshore requires strong connections between offshore wind farms and the energy island. Allowing the installation of electrolysers both onshore and offshore, as in *COMBI* and *STAKE*, we observe moderate direct cable connections from shore to islands. These cases allow for onshore electrolysis investments, which are assumed to be cheaper than building the assets offshore. The option of cheaper onshore electrolysis does not eliminate offshore electrolysis but lowers the capacity of energy-island-to-shore cable connections. However, by 2040, a strong offshore grid develops with capacities of 125 GW through cables in the sea. *BAU* leads to the highest curtailment and the lowest conventional technology use in 2040 because there is no electricity usage by electrolysers. Among the other cases, we see that eliminating onshore electrolysis leads to lower total electrolyser capacity being built and higher curtailment. The largest electrolyser capacities are built in 2040, in *COMBI*. This results in the highest hydrogen production and the lowest curtailment among all cases. We summarise our main findings as follows:

- Restricting electrolysis to offshore results in higher cable capacities connecting the energy islands to offshore wind farms.

- Limiting cable expansions according to project plans does not show much effect, and the results for *COMBI* and *STAKE* are very similar.
- Allowing investment in electrolysers both offshore and onshore lowers the curtailment of RES significantly.
- Electrolysis on the energy island of Bornholm (BHEI) is relevant only in the absence of onshore electrolysis or cable capacity expansion limitations.
- We observe higher use of nuclear power plants and biomass for electricity generation for cases with hydrogen production.

In addition to capacity expansions, the model shows trade patterns between the market zones. Interestingly, the energy islands in the North Sea both become net importers in all cases in the first two periods (but not in the third). The more the system changes towards a RES-based system the more electricity is used for direct consumption. In all cases, the same countries are net importers or net exporters: Germany, Poland, the UK, and Sweden are net exporters, and Belgium, the Netherlands, Denmark, the Czech Republic, Finland, and Norway are net importers. The wind park clusters built off the coasts of the respective countries require large investments in electricity infrastructure, and in the cases of Germany and the UK, the planned RES capacities exceeds what onshore grids can integrate (see Figure B.7 in the Appendix). Therefore, the wind parks are integrated with other markets through combined grid solutions, which connect two countries via a wind farm or other system assets, often also called hybrid assets (cf. Marten et al., 2018).

B.4.2 The Role of Electrolysers on Energy Islands

In this study, we analyse and discuss the trade-off between electricity and hydrogen infrastructure to integrate energy islands into the existing energy system. To identify possible trade-offs, we zoom in on the specific drivers of hydrogen production and on its location in the different cases. In general, electrolysis can cut down curtailment due to grid congestion and increase the use of available renewable energy technology.

Table B.5. Capacity factors of electrolysers ([%], weighted average).

	Offshore			Onshore		
	2030	2035	2040	2030	2035	2040
BAU	–	–	–	–	–	–
OFFSH	49.4	46.6	47.1	–	–	–
COMBI	51.6	50.3	51.8	41.8	39.7	39.8
STAKE	50.0	48.1	51.7	42.5	40.8	39.6

As described above, when we only allow electrolyser capacity investment offshore, on the energy islands, we see (1) higher system costs, (2) higher cable capacities in the seas in Northern Europe, and (3) higher curtailment than when we allow both offshore and onshore electrolysis. However, from Table B.3 we also see that generation from nuclear and biomass gets rises as the aggregated electrolyser capacity increases. The capacity factor is an important metric for the profitability potential of investments in and operation of electrolysers, independently of their placement. Conventional generation may be cheap enough to use for hydrogen production, such that the capacity factor increases. Cable connections between offshore wind clusters and energy islands are very large in the pure *OFFSH* case. Here, the additional cables also contribute to fuelling the electrolyser on the islands from onshore power generation, making offshore electrolysis more profitable. The offshore electrolysers operate at an average capacity factor of 49.4% in 2030 and 47.1% in 2040; see Table B.5. For the *COMBI* case with smaller cable connections, the offshore electrolysis capacity factors are slightly higher: 51.6% in 2030, 50.3% in 2035, and 51.8% in 2040. Onshore electrolysers, however, are operated at capacities of only around 40 % on average. The lower investment expenditures allow them to be profitable already at lower usage rates. In *STAKE*, electrolysis capacity and capacity factors both onshore and offshore are similar to those of *COMBI*. Our results are aligned with other sources indicating that electrolysers need a capacity factor of at least 35% to operate economically (IRENA, 2019).

A closer look at our results reveals a system of coordinated joint hydrogen and electricity production. So far in Europe, RES capacities have been mostly installed onshore (PV and wind), and at present offshore wind is typically connected radially to shore, not going through an energy island. Radially connecting offshore wind farms leads to higher RES availability and excess production onshore than if conversion assets are also placed offshore. Endogenising the decision about the placement of electrolysers results in a combination of large onshore capacities and about 10 GW of aggregated electrolysis capacity offshore. This finding differs from those of, for example, Gea Bermúdez et al. (2021) and Singlitico et al. (2021), who argue that offshore electrolysis will not play a role. An important contribution of our work is that our model includes a detailed onshore grid representation. In contrast, Gea Bermúdez et al. (2021) consider a zonal approach in their model, neglecting inner-zonal congestion and foresee large electricity import from southern Europe to reach electrolysers onshore along the coasts.

When the model allows it, most electrolysis capacity is installed onshore despite the lower capacity factors. At the same time, conventional generation is higher showing that it is economical to produce hydrogen from nuclear power, at least given its modest short-term marginal costs. In the model, the onshore grid capacities are fixed for the entire horizon, only including projects through the early 2030s that are already planned today. This possibly restricts access to RES from other geographic locations, having a two-fold impact: (1) the only technologies for stabilising the capacity factors are conventional power plants because they are effectively located with respect to current grid topology, and (2) curtailment cannot be lowered further due to onshore congestion. To address this limitation, we include a sensitivity analysis to assess the impact of onshore grid expansions on curtailment, conventional power plant use, and combined system costs.

B.4.3 Sensitivity Analysis

Here we perform a two-fold sensitivity analysis. The first part considers hydrogen and carbon prices. The second considers a fundamental basis of the model, the power network, and extends the onshore grid in an attempt to remove congestion. For the sensitivity analysis, we work with the setup and assumptions of the *COMBI* case of the main analysis, which had the lowest overall costs. Numeric results of the sensitivity analysis can be found in Table B.9 in the Appendix. The hydrogen and carbon prices used in the sensitivity analysis are presented in Table B.6.

Table B.6. Price parameter changes of the sensitivity analysis.

Prices in [€]	**CO_2 price**			**H_2 price**		
Scenario	2030	2035	2040	2030	2035	2040
initial configuration	80	120	160	108	108	108
lower H_2 price	80	120	160	81	81	81
higher H_2 price	80	120	160	135	135	135
higher CO_2 price	130	250	480	108	108	108
grid extension	80	120	160	108	108	108

B.4.3.1 Price Variations

In this first sensitivity analysis, we change the hydrogen price and the carbon price. First, we vary the hydrogen price by lowering and raising it by 25%, from the original €108 per MWh to €81 and €135, respectively, while keeping the CO_2 prices at the level of our original case study: €80, €120, and €160 respectively in years 2030, 2035, and 2040. We compare the results of our sensitivity analysis to *COMBI* of the main analysis and list the key values in Table B.9 in the Appendix.

A 25% lower hydrogen price results in 12% less aggregated electrolyser capacity with onshore electrolysis seeing the largest reduction. In addition, there is a lower direct cable capacity to shore when hydrogen prices are lower, as it is less interesting to bring power generated onshore to the islands. We still see 20 GW of offshore electrolysis, which implies that a larger part of the hydrogen is produced on the energy islands. In addition, conventional power production is lower in all years; see Figure B.5. This suggests that lower hydrogen prices decrease the value of hydrogen production and more renewable electricity is used for direct consumption resulting in more cable connections from the offshore wind clusters to shore and lower shares of fossil fuels and nuclear in the electricity mix. In the scenario with a 25% higher hydrogen price, we see the opposite. Higher aggregate electrolysis capacity is invested, and a relatively larger share is built onshore. Cable connections between island and shore and between wind clusters and shore are larger than in *COMBI* of our main analysis, which suggests that larger electricity cables can be refinanced by higher sale prices for hydrogen. Conventional power production is at a similar level in the main analysis and for low and high hydrogen prices. Similarly to the main analysis, in both cases conventional technology contributes to hydrogen production. When changing the hydrogen price, we observe that the lower price reduces electrolyser capacities and leads to less hydrogen production, see Figure B.5. The additional revenue from selling hydrogen makes mainly a combination of cable connections and onshore electrolysis economical. This lowers curtailment and results in more hydrogen production.

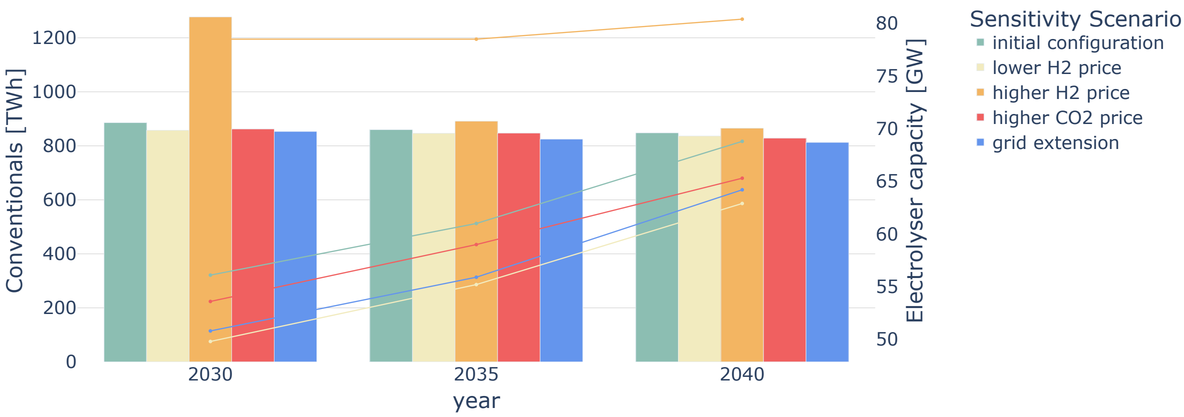


Figure B.5. Comparison of conventional power plant usage and electrolyser capacity in the different parts of the sensitivity analysis. Bars represent energy produced by conventionals and lines the electrolyser capacity developments over the years.

In the second sensitivity analysis, we change the CO_2 prices to €130 in 2030, €250 in 2035, and €480 in 2040 for each ton emitted. These values correspond to values in the openEntrance[11] 1.5°C scenario *Techno Friendly* (Auer et al., 2020). The higher carbon price not only increases system costs but leads to higher aggregate cable capacity between energy island and shore and between energy island and wind cluster from the first period onward (20 % more than in the main analysis from 2030 onward). With increasingly higher CO_2 prices, it would be valuable to invest earlier to increase the use of RES in the system and avoid carbon emissions as

[11]openEntrance is a research project mapping the energy system transformation to reach climate goals. See: openentrance.eu/.

much as possible. Electrolysis becomes slightly less attractive and is 5% lower each year compared to the main analysis. Figure B.5 shows that in comparison to the main analysis, an increased carbon price will lead to lower use of conventional generation but a similar aggregate electrolysis capacity. This scenario would very likely change further if it were combined with onshore grid expansion.

B.4.3.2 Onshore Network Capacities

From our main analysis, we can identify onshore power lines and interconnectors that are often congested. Figure B.7 in the Appendix shows the share of hours the depicted lines exceed 99% of their available capacity and we therefore consider them congested. For this sensitivity analysis, we assume a line to be limiting and prone to extension if the share of congested hours over the entire time horizon exceeds 70%. To relieve the bottlenecks, we add 20% multiplied by the share of congested hours to the existing capacity of each expanded line, consequently between 14% and 20%. We keep all other values and prices as in the original analysis. Here we present new results for the *COMBI* case in 2040 with an extended onshore network. Exogenously relieving the congestion from the grid this way lowers the combined investment and dispatch costs (5% below the main analysis) and leads to the lowest curtailment of all the cases. The reinforced grid leads to a similar integration of offshore resources by cable but a 10% lower electrolyser capacity; see Table B.9. Conventional power production is also at its lowest level because the larger transmission capacities bring larger shares of RES to consumption nodes and reduce curtailment. In suammery, onshore grid expansion leads to higher usage of RES and lower system costs (however not considering the cost of the exogenous grid extension) and has comparable system characteristics to *COMBI*.

B.4.4 Discussion of Model Assumptions

All the generation capacity in 2030 and the onshore grid are based on exogenous assumptions, as are the scaling paths to 2040. Not allowing endogenous capacity extension in the existing and projected power generation fleets restricts the construction of a theoretically optimal system design and influences the sizing of cables and electrolysers. For investment expenditures, we assume linearity, neglecting economies of scale and scope and learning rates. Furthermore, we assume that the islands are in the locations chosen by the reference projects, which may be a bias and could over- or underestimate the distance to onshore grid connection points. Offshore hydrogen production requires transportation by vessels or pipeline connections, which we include with a fixed cost markup per unit of capacity only. Together with the assumption of the islands' locations, this could slightly distort the costs and trade-off between hydrogen and electricity infrastructure. Hydrogen offtake is modelled via a fixed price rather than endogenised demand. But given the amount of hydrogen produced in the model compared to hydrogen demand projections for Europe, we view this assumption as uncritical. Furthermore, we have specifically addressed the sensitivity of hydrogen prices.

Last, we assume there will not be any integration with other sectors, such as heat—that is, no consideration of the use of excess heat from electrolysis. However, this is arguably equally relevant to the efficiency of onshore and offshore electrolysis. In the onshore case, it could increase the process efficiency by utilising heat to satisfy local heat demand. Offshore heat can be used for desalination processes to produce distilled water for electrolysis. The reduced time horizon and the reduced time series used for this model may affect the representative accuracy of demand and production patterns. Diving deep into the results and examining each capacity expansion, we also observe that there are some small cables (smaller than 500 MW) built between different offshore nodes. We assume that such small capacities would not be built in reality. For the combined case of onshore and offshore infrastructure, this could reduce the number of countries connecting directly to energy islands.

B.5 Conclusions

In this paper, we study the trade-off between investments in offshore electrolysers and in cable connections between energy islands and both offshore wind farms and shore, and more generally the trade-off between electricity transmission and hydrogen production infrastructures offshore. For the analysis, we developed an integrated capacity expansion and electricity dispatch model with power grid representation, which allows the energy islands to be connected by electricity cables to shore or to host hydrogen production.

In our main analysis, which adds hydrogen infrastructure investment options step by step to a system of electricity infrastructure only, we find that onshore electrolysis plays a larger role than its offshore counterpart. Offshore electrolysers, however, are especially relevant for using the electricity produced on energy islands, reducing curtailment, and keeping cable connections at a low level. All countries developing wind farms off their coasts build electrolysers onshore with capacities in the range of 5 to 10 GW. Based on our sensitivity analysis, we argue that this is also caused by congestion in the onshore grid. Nuclear and biomass also serve as fuels for hydrogen production, which is driven mainly by the low short-run marginal costs of these technologies and drive up capacity factors and thereby make larger electrolyser capacities profitable. Higher CO_2 prices drive out fossil-fuel-based hydrogen. This leads to lower hydrogen production and higher system costs overall. Exogenously reinforcing the network by increasing onshore grid capacities to remove congestion shows a higher usage of RES onshore to meet electricity demand rather than conversion.

In summary, investment in electrolysis capacity is sensitive to future hydrogen prices and the costs of technology. On the question of the trade-off between hydrogen and electricity infrastructure for energy islands, we conclude that electricity from offshore wind is more valuable than hydrogen for reducing carbon emissions from generation. Onshore electrolysis can benefit from efficiency gains through sector coupling and heat usage. In contrast, a lack of public acceptance of wind farms and electrolysis plants could drive up costs and favour offshore locations (Kaldellis et al., 2016). Offshore, on the other hand, excess heat could be used for seawater desalination (Wageningen University and Research, 2022). Onshore grid developments influence offshore development significantly, and the siting of electrolysers is sensitive to congestion in the grid. First mover expenses, however, will be higher, and the result on sizing presented here must be looked at with caution since they are initially a political decision that is not fully market-driven.

The presented analysis and results depend on assumptions and model limitations. We do not consider all the technical features and constraints of the generation technologies (e.g., unit commitment and ramping), and we disregard market sequences that might have an impact on trading activities, prices, and the availability of electricity in the system. The parameters for cost of electricity production, hydrogen infrastructure, and hydrogen markets are subject to large uncertainties, as is the production from renewable energy. This analysis could benefit from a stochastic approach to balance and hedge decisions considering uncertainty in production, prices, and technology cost development. Furthermore, the geographical scope of the model may be extended to include countries in the second row behind the seas, for example, France and also the Baltic countries. In the current results, offshore and onshore electrolysers are profitable and worth investing in at comparatively low capacity factors. Another source of distortion may be neglecting any costs for the energy island itself, for example, general costs for land use, or network charges and taxes. Further, we ignore the fact that cables come in predetermined sizes per unit and considering this, e.g., by using binary variables to reflect fixed costs and bundle sizes, may change the outcome. In addition, power prices in the current markets in Europe are not based on nodal pricing, which we use in this model. Generally, a zonal market set up will result in different market prices and may change the attractiveness of investing in electrolysers due to higher power purchasing prices. Being aware of the limitations in our approach, we do believe that the insights are generalisable beyond the limits of the specific case studies that we have analysed. Offshore power transmission and hydrogen production infrastructure complement each other in bringing energy to shore, mitigating RES intermittency, and reducing curtailment. Both will have a significant role in the integration of offshore wind energy into the north-western European energy system.

References

Agora Energiewende & AFRY Management Consulting. (2021). *No-regret hydrogen: Charting early steps for H\textsubscript2 infrastructure in Europe.* Agora Energiewende. https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf

Alharbi, H., & Bhattacharya, K. (2014). Optimal sizing of battery energy storage systems for microgrids. *2014 IEEE Electrical Power and Energy Conference*, 275–280. https://doi.org/10.1109/EPEC.2014.44

Auer, H., Crespo del Granado, P., Oei, P.-Y., Hainsch, K., Löffler, K., Burandt, T., Huppmann, D., & Grabaak, I. (2020). Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE. *e & i Elektrotechnik und Informationstechnik*, *137*(7), 346–358. https://doi.org/10.1007/s00502-020-00832-7

Babarit, A., Gilloteaux, J.-C., Clodic, G., Duchet, M., Simoneau, A., & Platzer, M. F. (2018). Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters. *International Journal of Hydrogen Energy*, *43*(15), 7266–7289. https://doi.org/10.1016/j.ijhydene.2018.02.144

Backe, S., Skar, C., del Granado, P. C., Turgut, O., & Tomasgard, A. (2022). EMPIRE: An open-source model based on multi-horizon programming for energy transition analyses. *SoftwareX*, *17*, 100877. https://doi.org/10.1016/j.softx.2021.100877

Bristowe, G., & Smallbone, A. (2021). The key techno-economic and manufacturing drivers for reducing the cost of power-to-gas and a hydrogen-enabled energy system. *Hydrogen*, *2*(3), 273–300. https://doi.org/10.3390/hydrogen2030015

Brunner, C., Michaelis, J., & Möst, D. (2015). Competitiveness of different operational concepts for power-to-gas in future energy systems. *Zeitschrift für Energiewirtschaft*, *39*(4), 275–293. https://doi.org/10.1007/s12398-015-0165-0

Bundesnetzagentur. (2021). *Monitoringbericht 2021*. https://www.bundesnetzagentur.de/SharedDocs/Mediathek/Monitoringberichte/Monitoringbericht_Energie2021.pdf?___blob=publicationFile&v=3

Castillo, A., & Gayme, D. F. (2014). Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management*, *87*, 885–894. https://doi.org/https://doi.org/10.1016/j.enconman.2014.07.063

COWI. (2021). *Cost benefit analyse og klimaaftryk af energiøer i Nordsøen og Østersøen*. https://ens.dk/sites/ens.dk/files/Vindenergi/a209704-001_cost_benefit_analyse_endelig_version.pdf

Danish Energy Agency. (2022). Technology Data for Renewable Fuels. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

Dedecca, J. G., Hakvoort, R. A., & Herder, P. M. (2019). The integrated offshore grid in Europe: Exploring challenges for regional energy governance. *Energy Research & Social Science*, *52*, 55–67. https://doi.org/10.1016/j.erss.2019.02.003

Dinh, V. N., Leahy, P., McKeogh, E., Murphy, J., & Cummins, V. (2021). Development of a viability assessment model for hydrogen production from dedicated offshore wind farms. *International Journal of Hydrogen Energy*, *46*(48), 24620–24631. https://doi.org/10.1016/j.ijhydene.2020.04.232

Egerer, J., Kunz, F., & Hirschhausen, C. v. (2013). Development scenarios for the North and Baltic Seas Grid – A welfare economic analysis. *Utilities Policy*, *27*, 123–134. https://doi.org/10.1016/j.jup.2013.10.002

European Commission, Joint Research Centre (JRC). (2019). JRC Hydro-power database. http://data.europa.eu/89h/52b00441-d3e0-44e0-8281-fda86a63546d

Finck, R. (2021). Impact of flow based market coupling on the European electricity markets. *Sustainability Management Forum*, *29*(2), 173–186. https://doi.org/10.1007/s00550-021-00520-w

Gea Bermúdez, J., Pedersen, R. B. B., Koivisto, M. J., Kitzing, L., & Ramos, A. (2021). *Going offshore or not: Where to generate hydrogen in future integrated energy systems?* (preprint). https://doi.org/10.36227/techrxiv.14806647.v2

Gerbaulet, C., & Lorenz, C. (2017). *dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market* (Data Documentation No. 88). DIW Berlin, German Institute for Economic Research. https://EconPapers.repec.org/RePEc:diw:diwddc:dd88

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, *4*(3), 216–222. https://doi.org/10.1038/s41560-019-0326-1

Göke, L., & Kendziorski, M. (2022). Adequacy of time-series reduction for renewable energy systems. *Energy*, *238*(121701), 1–14. https://doi.org/10.1016/j.energy.2021.121701

Gorenstein Dedecca, J., Hakvoort, R. A., & Herder, P. M. (2017). Transmission expansion simulation for the European Northern Seas offshore grid. *Energy*, *125*, 805–824. https://doi.org/10.1016/j.energy.2017.02.111

Hagspiel, S., Jägemann, C., Lindenberger, D., Brown, T., Cherevatskiy, S., & Tröster, E. (2014). Cost-optimal power system extension under flow-based market coupling. *Energy*, *66*, 654–666. https://doi.org/10.1016/j.energy.2014.01.025

Hameer, S., & van Niekerk, J. L. (2015). A review of large-scale electrical energy storage: This paper gives a broad overview of the plethora of energy storage. *International Journal of Energy Research*, *39*(9), 1179–1195. https://doi.org/10.1002/er.3294

Haumaier, J., Hauser, P., Hobbie, H., & Möst, D. (2020). Grünes Gas für die Gaswirtschaft – Regionale Power-to-Gas-Potentiale aus onshore-Windenergie in Deutschland. *Zeitschrift für Energiewirtschaft*, *44*(2), 61–83. https://doi.org/10.1007/s12398-020-00274-w

Hoffmann, M., Kotzur, L., Stolten, D., & Robinius, M. (2020). A review on time series aggregation methods for energy system models. *Energies*, *13*(3), 641. https://doi.org/10.3390/en13030641

Hörsch, J., Hofmann, F., Schlachtberger, D., & Brown, T. (2018). PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strategy Reviews*, *22*, 207–215. https://doi.org/10.1016/j.esr.2018.08.012

Hörsch, J., Ronellenfitsch, H., Witthaut, D., & Brown, T. (2018). Linear optimal power flow using cycle flows. *Electric Power Systems Research*, *158*, 126–135. https://doi.org/10.1016/j.epsr.2017.12.034

IRENA. (2019). *Hydrogen: A renewable energy perspective*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf

Jansen, M., Duffy, C., Green, T. C., & Staffell, I. (2022). Island in the Sea: The prospects and impacts of an offshore wind power hub in the North Sea. *Advances in Applied Energy*, *6*, 100090. https://doi.org/10.1016/j.adapen.2022.100090

Joos, M., & Staffell, I. (2018). Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. *Renewable and Sustainable Energy Reviews*, *86*, 45–65. https://doi.org/10.1016/j.rser.2018.01.009

Kaldellis, J., Apostolou, D., Kapsali, M., & Kondili, E. (2016). Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. *Renewable Energy*, *92*, 543–556. https://doi.org/10.1016/j.renene.2016.02.018

Kotzur, L., Markewitz, P., Robinius, M., & Stolten, D. (2018). Impact of different time series aggregation methods on optimal energy system design. *Renewable Energy*, *117*, 474–487. https://doi.org/10.1016/j.renene.2017.10.017

Kristiansen, M., Korpås, M., & Farahmand, H. (2018). Towards a fully integrated North Sea offshore grid: An engineering-economic assessment of a power link island. *WIREs Energy and Environment*, *7*(4). https://doi.org/10.1002/wene.296

Lauria, S., Schembari, M., Palone, F., & Maccioni, M. (2016). Very long distance connection of gigawatt-size offshore wind farms: Extra high-voltage AC versus high-voltage DC cost comparison. *IET Renewable Power Generation*, *10*(5), 713–720. https://doi.org/10.1049/iet-rpg.2015.0348

Leuthold, F. U., Weigt, H., & von Hirschhausen, C. (2008). ELMOD - A Model of the European Electricity Market. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1169082

Marten, A.-K., Akmatov, V., Sørensen, T. B., Stornowski, R., Westermann, D., & Brosinsky, C. (2018). Kriegers flak-combined grid solution: Coordinated cross-border control of a meshed HVAC/HVDC offshore wind power grid. *IET Renewable Power Generation*, *12*(13), 1493–1499. https://doi.org/10.1049/iet-rpg.2017.0792

Meier, K. (2014). Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: Techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology. *International Journal of Energy and Environmental Engineering*, *5*(2-3), 104. https://doi.org/10.1007/s40095-014-0104-6

Nahmmacher, P., Schmid, E., & Knopf, B. (2014). *Documentation of LIMES-EU: A long-term electricity system model for europe*. Potsdam Institute for Climate Impact Research. https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/limes/limes-documentation-april-2020

Pfenninger, S., & Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, *114*, 1251–1265. https://doi.org/10.1016/j.energy.2016.08.060

Pilpola, S., & Lund, P. D. (2019). Different flexibility options for better system integration of wind power. *Energy Strategy Reviews*, *26*, 100368. https://doi.org/10.1016/j.esr.2019.100368

Poncelet, K., Hoschle, H., Delarue, E., Virag, A., & Drhaeseleer, W. (2017). Selecting representative days for capturing the implications of integrating intermittent renewables in generation expansion planning problems. *IEEE Transactions on Power Systems*, *32*(3), 1936–1948. https://doi.org/10.1109/TPWRS.2016.2596803

Schlachtberger, D., Brown, T., Schramm, S., & Greiner, M. (2017). The benefits of cooperation in a highly renewable European electricity network. *Energy*, *134*, 469–481. https://doi.org/10.1016/j.energy.2017.06.004

Schlecht, I., & Simic, M. (2020). Renewable power plants. https://doi.org/10.25832/RENEWABLE_POWER_PLANTS/2020-08-25

Schütz, T., Schraven, M. H., Fuchs, M., Remmen, P., & Müller, D. (2018). Comparison of clustering algorithms for the selection of typical demand days for energy system synthesis. *Renewable Energy*, *129*, 570–582. https://doi.org/10.1016/j.renene.2018.06.028

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition*, *1*, 100005. https://doi.org/10.1016/j.rset.2021.100005

Staffell, I., & Pfenninger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, *114*, 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068

Strbac, G., Moreno Vieyra, R., Konstantelos, I., Aunedi, M., & Pudjianto, D. (2014). *Strategic Development of North Sea Grid Infrastructure to Facilitate Least-Cost Decarbonisation*. Imperial College London. https://doi.org/10.25561/28452

Tosatto, A., Beseler, X. M., Østergaard, J., Pinson, P., & Chatzivasileiadis, S. (2022). North Sea Energy Islands: Impact on national markets and grids. *Energy Policy*, *167*, 112907. https://doi.org/10.1016/j.enpol.2022.112907

Trötscher, T., & Korpås, M. (2011). A framework to determine optimal offshore grid structures for wind power integration and power exchange: A framework to determine optimal offshore grid structures. *Wind Energy*, *14*(8), 977–992. https://doi.org/10.1002/we.461

Victoria, M., Zhu, K., Brown, T., Andresen, G. B., & Greiner, M. (2020). Early decarbonisation of the European energy system pays off. *Nature Communications*, *11*(1), 6223. https://doi.org/10.1038/s41467-020-20015-4

Wageningen University and Research. (2022). Green hydrogen at sea cheaper and more sustainable. https://www.wur.nl/en/research-results/research-institutes/food-biobased-research/show-fbr/green-hydrogen-at-sea-cheaper-and-more-sustainable.htm

Weibezahn, J., Kendziorski, M., Kramer, H., & von Hirschhausen, C. (2020). The impact of transmission development on a 100% renewable electricity supply—a spatial case study on the german power system. In M. R. Hesamzadeh, J. Rosellón, & I. Vogelsang (Eds.), *Transmission Network Investment in Liberalized Power Markets* (pp. 453–474). Springer International Publishing. https://doi.org/10.1007/978-3-030-47929-9_15

Weinhold, R. (2021). Evaluating Policy Implications on the Restrictiveness of Flow-based Market Coupling with High Shares of Intermittent Generation: A Case Study for Central Western Europe. https://doi.org/10.48550/ARXIV.2109.04940

Zatti, M., Gabba, M., Freschini, M., Rossi, M., Gambarotta, A., Morini, M., & Martelli, E. (2019). K-MILP: A novel clustering approach to select typical and extreme days for multi-energy systems design optimization. *Energy*, *181*, 1051–1063. https://doi.org/10.1016/j.energy.2019.05.044

Zhang, H., Tomasgard, A., Knudsen, B. R., Svendsen, H. G., Bakker, S. J., & Grossmann, I. E. (2022). Modelling and analysis of offshore energy hubs. *Energy*, *261*, 125219. https://doi.org/10.1016/j.energy.2022.125219

Appendix to Paper B

Model Description

Table B.7 presents the nomenclature used in the paper. Sets are expressed in script, parameters in lowercase, and variables in uppercase italic letters.

Table B.7. Designated sets, parameters, and variables of the mathematical model.

Sets	
$\mathcal{N}$	set of nodes: n, m
$\mathcal{G}$	set of conventional power plants: g
$\mathcal{R}$	set of RES: r
$\mathcal{W}$	set of reservoirs: w
$\mathcal{S}$	set of storages: s
$\mathcal{E}$	set of electrolyser: e
$\mathcal{A}$	set of AC transmission lines: $a \in (n, m)$
$\mathcal{D}$	set of DC transmission lines $d \in (n, m)$
$\mathcal{L}$	subset of $\mathcal{D}$, lines to the EI $l \in (n, m)$
$\mathcal{T}$	set of time slices: t
$\mathcal{Y}$	set of years: y
$\mathcal{O}$	set of $\mathcal{A} - \mathcal{N} + 1$ cycles: o
$\mathcal{Z}$	set of bidding zones: z
Parameters	
$\alpha/\beta/\gamma_{n,y}$	scaling factor for capacity development of conventional generation/RES/demand
δ	scaling factor for time series reduction
$\eta^{\mathrm{E/S}}$	efficiency of electrolyser/storage units
$\mathrm{b}_{n,a}$	incidence matrix entry of node n at line a
$\mathrm{h}_{o,a}$	cycle incidence matrix entry of cycle o and line a
c^{D}	penalty for loss of load
$\mathrm{c}^{\mathrm{M}}_{g,y}$	marginal cost of power plant in €/MWh$_{\mathrm{el}}$
$\mathrm{c}^{\mathrm{O}}_{e}$	operational and maintenance cost for electrolyser in % of capital expenses
c^{S}	costs for storage depletion
c^{E}	cost of electrolyser in €/MW
c^{L}	cost for transmission line in €/(MW·km)
$\mathrm{d}_{n,t,y}$	demand at node n of year y
j_{y}	discount factor of year y
$\mathrm{k}^{\mathrm{E/L}}$	annuity factor electrolyser/line
g_{i}	length of the electricity line i in km
s^{+}_{s}	capacity of storage s in MWh$_{\mathrm{el}}$
f^{+}_{d}	DC line capacity in MW$_{\mathrm{el}}$
f^{+}_{a}	AC line capacity in MW$_{\mathrm{el}}$
$\mathrm{p}^{+}_{g/r/s}$	maximum power generation of conventional generation/RES/storage in MW$_{\mathrm{el}}$
p^{+}_{z}	maximum energy production from hydro reservoir in MWh$_{\mathrm{el}}$
p^{-}_{s}	maximum power consumption of storage in MW$_{\mathrm{el}}$

q	discount factor (1 + interest rate)
$\mathrm{r}_e^{\mathrm{E}}$	revenue from selling hydrogen in €/MWh
v	TRM between 0 and 1
x_a	reactance of AC line a in Ω

Decision Variables

$I_{e,y}^{\mathrm{E}}$	installed capacity of the electrolyser e in year y in $\mathrm{MW_{el}}$
$I_{l,y}^{\mathrm{L}}$	installed capacity of the electricity connection line l to the EI in year y in $\mathrm{MW_{el}}$
$F_{a,t,y}^{\mathrm{A}}$	AC line flow of line a in $\mathrm{MW_{el}}$
$F_{l,t,y}^{\mathrm{L}}$	EI connection line flow of line l in $\mathrm{MW_{el}}$
$F_{d,t,y}^{\mathrm{D}}$	DC line flow of line d in $\mathrm{MW_{el}}$
$S_{s,t,y}^{\mathrm{L}}$	storage level of storage unit in $\mathrm{MWh_{el}}$
$P_{g,t,y}^{\mathrm{C}}$	generated conventional power in $\mathrm{MW_{el}}$
$P_{n,t,y}^{\mathrm{D-}}$	demand loss of load at node n in $\mathrm{MW_{el}}$
$P_{r,t,y}^{\mathrm{R}}$	generated RES power in $\mathrm{MW_{el}}$
$P_{w,t,y}^{\mathrm{W}}$	generated power from reservoir in $\mathrm{MW_{el}}$
$P_{n,t,y}^{\mathrm{R-}}$	RES curtailment at node n in $\mathrm{MW_{el}}$
$P_{e,t,y}^{\mathrm{E}}$	electrical power to the electrolyser in $\mathrm{MW_{el}}$
$S_{s,t,y}^{\mathrm{D}}$	generated power from storage discharge in $\mathrm{MW_{el}}$
$S_{s,t,y}^{\mathrm{C}}$	power withdrawal from storage charge in $\mathrm{MW_{el}}$

Objective. The objective function Eq. (B.1) minimises the cost for dispatch and capacity extensions. In the dispatch we include marginal costs c^{M} for dispatching thermal power plants P^{C}, cost c^{D} for curtailing load $P^{\mathrm{D-}}$, and a discharge penalty c^{S} for storage P^{S}. In addition, we subtract income r^{E} from producing hydrogen P^{E}. RES do not incur marginal costs. Investments in electrolysers I^{E} and connecting power lines I^{L} are allowed at specific costs $\mathrm{c}^{\mathrm{E/L}}$ adjusted by an annuity factor $\mathrm{k}^{\mathrm{E/L}}$ (Eq. (B.2)). For electrolysers we include annual operation and maintenance costs c_e^{O}.

$$\begin{aligned}\min \sum_y \Bigg[\delta \cdot \Bigg(&\sum_t \sum_g \mathrm{c}_{g,y}^{\mathrm{M}} \cdot P_{g,t,y}^{\mathrm{C}} + \mathrm{c}^{\mathrm{D}} \cdot \sum_t \sum_n P_{n,t,y}^{\mathrm{D-}} \\ &+\mathrm{c}^{\mathrm{S}} \cdot \sum_t \sum_s P_{s,t,y}^{\mathrm{S}} - \sum_t \sum_e \mathrm{r}_e^{\mathrm{E}} \cdot P_{e,t,y}^{\mathrm{E}} \cdot \eta^{\mathrm{E}}\Bigg) \\ &+\mathrm{c}^{\mathrm{E}} \cdot \sum_e (\mathrm{k}^{\mathrm{E}} + \mathrm{c}_e^{\mathrm{O}}) \cdot I_{e,y}^{\mathrm{E}} + \mathrm{k}^{\mathrm{L}} \cdot \mathrm{c}^{\mathrm{L}} \cdot \sum_l \mathrm{g}_l \cdot I_{l,y}^{\mathrm{L}}\Bigg] \cdot \mathrm{j}_y\end{aligned} \tag{B.1}$$

$$\mathrm{k}^{\mathrm{E/L}} = \frac{q}{1 - \left(\frac{1}{1+q}\right)^{\mathrm{Lifetime}}} \tag{B.2}$$

The model runs for a reduced time series. δ scales the representative days to the full set of 8760 time steps and is consequently approximated to be $\frac{8760}{t}$ rounded to ten decimals. For the horizon of multiple (five-year) periods y, we use a discount factor j_y (Eq. (B.3)) to discount all costs to the reference period.

$$\mathrm{j}_y = \frac{1}{(1+q)^{5\cdot y}} \tag{B.3}$$

Energy Balance. We limit the model by a set of constraints. Eq. (B.4) introduces the supply-demand balance for each node: the sum of the power generation by conventional power plants P^{C}, RES P^{R}, reservoirs P^{W}, storage flows $S^{\mathrm{C/D}}$, electrolyser consumption P^{E}, and load d must always equal the nodal power injections F by the connected AC and DC transmission lines. A variable for loss of load $P^{\mathrm{D-}}$ allows load shedding.

$$\begin{aligned}
&\sum_{g\in\Delta_n^G} P^{\mathrm{C}}_{g,t,y} + \sum_{r\in\Delta_n^R} P^{\mathrm{R}}_{r,t,y} + \sum_{w\in\Delta_z^W} P^{\mathrm{W}}_{w,t,y} \\
&+ \sum_{s\in\Delta_n^S} S^{\mathrm{D}}_{s,t,y} - \sum_{s\in\Delta_n^S} S^{\mathrm{C}}_{s,t,y} - \sum_{e\in\Delta_n^E} P^{\mathrm{E}}_{e,t,y} \\
&+ \sum_m F^{\mathrm{D}}_{m,n,t,y} - \sum_m F^{\mathrm{D}}_{n,m,t,y} + \sum_a \mathrm{b}_{n,l} \cdot F^{\mathrm{A}}_{l,t,y} \\
&= \gamma_y \cdot d_{n,t,y} - P^{\mathrm{D-}}_{n,t,y} \qquad n \in N,\, t \in T, y \in Y
\end{aligned} \tag{B.4}$$

Investments. The DC power connections to the energy islands are endogenously decided by the model. Flow F^{L} is limited by the installed capacities (Eq. (B.5) and Eq. (B.6)). Line capacities can only be extended and Eq. (B.7) ensures that no decommissioning should take place. On all lines, there is a transmission reliability margin v deducted from full capacity.

$$F^{\mathrm{L}}_{l,t,y} \leq I^{\mathrm{L}}_{l,y} \cdot (1 - \mathrm{v}) \qquad l \in \mathcal{L}, t \in T, y \in \mathcal{Y} \tag{B.5}$$

$$F^{\mathrm{L}}_{l,t,y} \geq -\left[I^{\mathrm{L}}_{l,y} \cdot (1 - \mathrm{v})\right] \qquad l \in \mathcal{L}, t \in T, y \in \mathcal{Y} \tag{B.6}$$

$$0 \leq I^{\mathrm{L}}_{l,y-1} \leq I^{\mathrm{L}}_{l,y} \qquad l \in \mathcal{L}, y \in \mathcal{Y} \tag{B.7}$$

Electrolyser capacity can only be expanded in the next period and cannot be decommissioned, Eq. (B.8).

$$0 \leq I^{\mathrm{E}}_{e,y-1} \leq I^{\mathrm{E}}_{e,y} \quad e \in \mathcal{E}, y \in \mathcal{Y} \tag{B.8}$$

Operational Constraints. Conventional power plants P^{C} and RES P^{R} including run-of-river hydropower can only operate below their maximum electricity output or installed capacities p^{+}, respectively. Due to multi-period optimisation, scaling factors α and β adjust the installed capacities, see Eq. (B.9) and Eq. (B.10).

$$0 \leq P^{\mathrm{C}}_{g,t,y} \leq \alpha_y \cdot \mathrm{p}^{+}_{g} \quad g \in \mathcal{G}, t \in \mathcal{T}, y \in \mathcal{Y} \tag{B.9}$$

$$0 \leq P^{\mathrm{R}}_{r,t,y} \leq \beta_y \cdot \mathrm{p}^{+}_{r,t} \quad r \in \mathcal{R}, t \in \mathcal{T}, y \in \mathcal{Y} \tag{B.10}$$

For evaluation purposes the RES curtailment $P^{\mathrm{R}-}$ is defined as the difference between the possible RES generation p^{+} and the actual dispatch P^{R}.

$$0 \leq P^{\mathrm{R}-}_{n,t,y} = \beta_y \cdot \mathrm{p}^{+}_{r} - P^{\mathrm{R}}_{r,t,y} \quad r \in \mathcal{R}, t \in \mathcal{T}, y \in \mathcal{Y} \tag{B.11}$$

Additionally, hydropower reservoirs are limited in their maximum production in the chosen period and bidding zone to ensure a more realistic representation of water availability, Eq. (B.12).

$$\sum_{t \in \mathcal{T}} \sum_{w \in \Delta^{W}_{z}} P^{\mathrm{W}}_{w,t,y} \leq \mathrm{p}^{+}_{z} \qquad \forall\ z \in Z, y \in Y \tag{B.12}$$

Storage (i.e., batteries and pumped hydropower) usage $S^{\mathrm{C/D}}$ is limited by maximum charge p^{+}_{s} (Eq. (B.13)) and discharge p^{-}_{s} (Eq. (B.14)) rates as well as an upper capacity limit s^{+}_{s} (Eq. (B.15)). Eq. (B.16) defines the filling level of the storage S^{L} taking into account efficiency losses. Eq. (B.17) and Eq. (B.18) fix the starting and ending levels of a storage to half its capacity, respectively.

$$
\begin{aligned}
0 \leq S^{\mathrm{C}}_{s,t,y} &\leq \mathrm{p}^{+}_{s} && s \in \mathcal{S}, t \in \mathcal{T} : t > 1, y \in \mathcal{Y} && \text{(B.13)}\\
0 \leq S^{\mathrm{D}}_{s,t,y} &\leq \mathrm{p}^{-}_{s} && s \in \mathcal{S}, t \in \mathcal{T} : t > 1, y \in \mathcal{Y} && \text{(B.14)}\\
0 \leq S^{\mathrm{L}}_{s,t,y} &\leq \mathrm{s}^{+}_{s} && s \in \mathcal{S}, t \in \mathcal{T} : t > 1, y \in \mathcal{Y} && \text{(B.15)}\\
S^{\mathrm{L}}_{s,t,y} &= S^{\mathrm{L}}_{s,t-1,y} - S^{\mathrm{D}}_{s,t,y} + \eta^{\mathrm{S}} \cdot S^{\mathrm{C}}_{s,t,y} && s \in \mathcal{S}, t \in \mathcal{T} : t > 1, y \in \mathcal{Y} && \text{(B.16)}\\
S^{\mathrm{L}}_{s,t,y} &= 0.5 \cdot \mathrm{s}^{+}_{s} - S^{\mathrm{D}}_{s,t,y} + \eta^{\mathrm{S}} \cdot S^{\mathrm{C}}_{s,t,y} && s \in \mathcal{S}, t \in \mathcal{T} : t = 1, y \in \mathcal{Y} && \text{(B.17)}\\
S^{\mathrm{L}}_{s,t,y} &= 0.5 \cdot \mathrm{s}^{+}_{s} && s \in \mathcal{S}, t \in \mathcal{T} : t = 8760, y \in \mathcal{Y} && \text{(B.18)}
\end{aligned}
$$

For the electrolysis capacity built in the model, there is a maximum power inflow restriction constraint to the maximum installed capacity (Eq. (B.19)).

$$0 \leq P^{E}_{e,t,y} \leq I^{\mathrm{E}}_{e,y} \quad e \in \mathcal{E}, t \in \mathcal{T}, y \in \mathcal{Y} \tag{B.19}$$

Lost load can never exceed the actual load of the node (Eq. (B.20))

$$0 \leq P^{\mathrm{D}-}_{n,t,y} \leq \gamma_{y} \cdot d^{\mathrm{load}}_{n,t,y} \quad n \in N,\, t \in T, y \in Y \tag{B.20}$$

Network Representation. To represent power flows in the AC network, we use the cycle-based formulation of Kirchhoff's voltage law, which leads to the sum of all potential changes in each cycle to be zero (Hörsch, Ronellenfitsch, et al., 2018). We take the cycle incidence matrix $\mathrm{h}_{o,l}$ and the line reactance x_{a} to calculate the line flows F^{A} and obtain a representation in our model as in Eq. (B.21).

$$\sum_{l} \mathrm{h}_{o,l} \cdot \mathrm{x}_{a} \cdot F^{\mathrm{A}}_{a,t,y} = 0 \quad o \in O,\, t \in T, y \in Y \tag{B.21}$$

The flows F on the AC and DC lines in the model must then not exceed thermal capacity limits p^{+} reduced by the transmission reliability margin v. This holds true for positive and negative flow directions (Eq. (B.22)-Eq. (B.25)).

$$
\begin{aligned}
F^{\mathrm{A}}_{a,t,y} &\leq \mathrm{p}^{+}_{a} \cdot (1-\mathrm{v}) && l \in \mathcal{A}, t \in \mathcal{T}, y \in \mathcal{Y} && \text{(B.22)}\\
F^{\mathrm{A}}_{a,t,y} &\geq -\big[\mathrm{p}^{+}_{a} \cdot (1-\mathrm{v})\big] && l \in \mathcal{A}, t \in \mathcal{T}, y \in \mathcal{Y} && \text{(B.23)}\\
F^{\mathrm{D}}_{d,t,y} &\leq \mathrm{p}^{+}_{d} \cdot (1-\mathrm{v}) && d \in (\mathcal{D} \setminus \mathcal{L}), t \in \mathcal{T}, y \in \mathcal{Y} && \text{(B.24)}\\
F^{\mathrm{D}}_{d,t,y} &\geq -\big[\mathrm{p}^{+}_{d} \cdot (1-\mathrm{v})\big] && d \in (\mathcal{D} \setminus \mathcal{L}), t \in \mathcal{T}, y \in \mathcal{Y} && \text{(B.25)}
\end{aligned}
$$

In the past, national grid operators defined net transfer capacity margins limiting transfers between countries and allowing the national entities to adjust to their local optimum, which is especially problematic in congestion management because it does not fully utilise the physical potential (Hagspiel et al., 2014). Additionally, the concept lacks a mechanism for fast net transfer capacity adjustments to the weather and generation situation (Finck, 2021). Net transfer capacity mechanisms have been gradually replaced since 2015 with flow-based market coupling (FBMC) and brought higher capacity allocations to the system. This utilises the infrastructure to a higher degree and is consequently more efficient. However, transmission system operators (TSOs) restrict commercial exchange to solve national grid congestion leading to lower than optimal capacity integration (Weinhold, 2021). Naturally, this is not optimal in a European context. For reasons of simplification, with the chosen nodal European dispatch, we neglect national considerations for the dispatch.

General Assumptions. Given the trade-off between complexity, accuracy, and computation time the model does not predict the full European generation landscape in the investigated years but sketches scenarios under given assumptions. The assumptions are simplified and subject to high uncertainty, which is not accounted for in this model. Furthermore, political decisions affect the future generation and transmission landscape and are subject to social and economic considerations of the actors involved. The most critical assumptions are listed and shortly explained in the following.

- **Construction time:** any time between investment decision and completion is neglected in the model.
- **Cross border exchange:** the model does not allow for exchange with nodes or zones that are not included. Market boundaries are not considered as we solve the model on a nodal basis.
- **Grid:** power lines are aggregated to create a less complex grid structure and prevent loop flows. A TRM is introduced as in Hörsch, Ronellenfitsch, et al. (2018). Line losses are neglected.
- **Ramping:** no ramping of any technology is considered in the model.

- **Must-run obligation and unit commitment:** we disregard unit commitment and must-run obligations of for example combined heat and power plants (CHPs).
- **Storage:** hydrogen storage is neglected.
- **Hydrogen:** hydrogen is expected to be sold at a fixed price. Any considerations regarding transport and consumption are not reflected.
- **Economics:** interest rate and cost parameters are assumed to be constant over time.
- **Decommissioning:** decommissioning does not take place or incurs a cost.

Hydrogen Price Predictions

Hydrogen price forecasts vary significantly depending on the sources. Table B.8 provides an overview about different price ranges.

Table B.8. Hydrogen prices from electrolysis.

Source	Base year	Hydrogen price [€/kg]
Dinh et al. (2021)	2030	5
Haumaier et al. (2020)	2020	6.2–20.2
Meier (2014)	2014	5.2–106.1
Brunner et al. (2015)	2015	1.4–6.8
Bristowe and Smallbone (2021)	2030	3.4–5.7
Babarit et al. (2018)	2025	2.34
ICCT[a]	2050	6.79[b]

[a] Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe. The International Council on Clean Transportation (2020)
[b] Median of European grid connected projects, collected from public sources

Further Results

Table B.9. Key values for the sensitivity analysis. Offshore and onshore electrolysis and non-restricted cable extension included.

		Objective value	Aggregated electrolyser capacity [GW]			Aggregated cable capacity [GW]			Curtailment [TWh]			Conventional generation [TWh]		
			2030	**2035**	**2040**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**	**2030**	**2035**	**2040**
COMBI	**Offshore**	1.12E+11	21.5	21.5	21.5	11.7	14.2	16.8	1.6	1.3	1.2	–	–	–
	Onshore		34.6	39.6	47.3	7.7	8.7	9.4	7.3	12.3	18.5	474.9	452.1	496.2
Low H_2	**Offshore**	2.08E+11	19.9	19.9	20.0	14.0	15.9	17.4	1.6	1.3	1.2	–	–	–
	Onshore		29.9	35.3	42.9	8.9	9.9	10.7	7.3	12.3	18.5	474.9	452.1	496.2
High H_2	**Offshore**	1.23E+11	20.9	20.9	20.9	13.3	13.3	15.9	1.6	1.3	1.2	–	–	–
	Onshore		57.5	57.5	59.5	10.8	10.8	11.1	7.3	12.3	18.5	474.9	452.1	496.2
High CO_2	**Offshore**	2.08E+11	20.3	20.3	20.3	15.5	19.0	25.1	1.5	1.1	0.6	–	–	–
	Onshore		33.3	38.7	45.0	9.9	12.3	13.8	7.6	14.1	23.7	453.7	443.5	434.1
Network	**Offshore**	1.07E+11	20.4	20.4	20.4	11.3	14.9	18.0	1.4	0.9	0.9	–	–	–
	Onshore		30.4	35.5	43.8	8.3	9.2	9.6	7.2	12.0	18.0	440.9	416.1	461.7

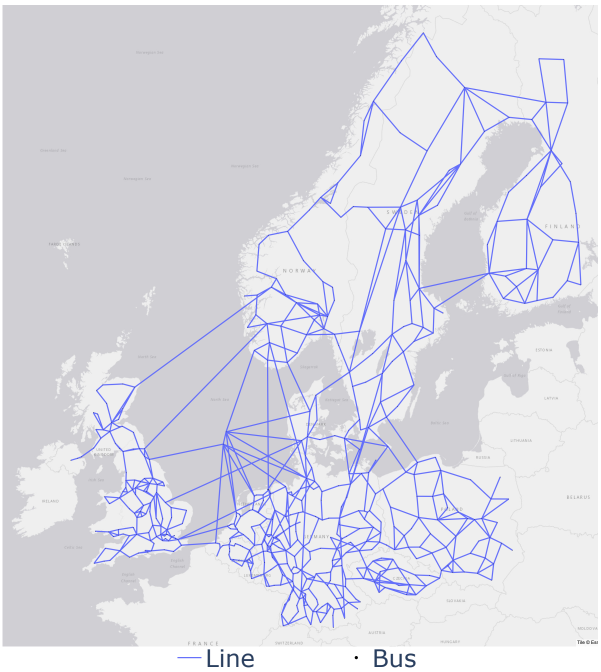


Figure B.6. Representation of the grid including all possible connections between energy island and shore.

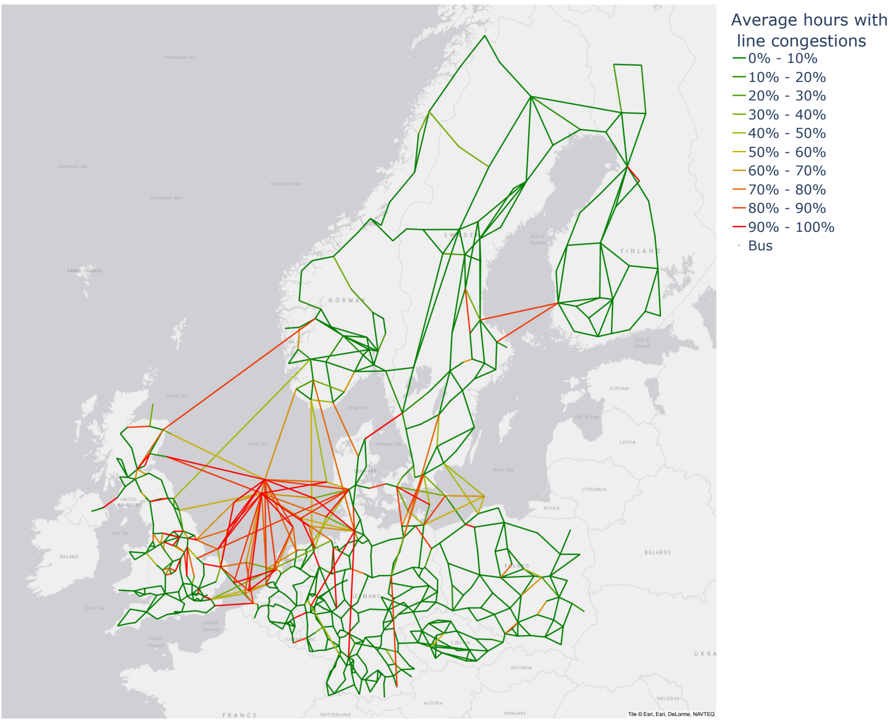


Figure B.7. Line congestions in the main analysis.

Table B.10. Conventional power plant use in TWh the sensitivity analysis.

		Main analysis			High CO_2 price			Low H_2 price			High H_2 price			Network expansion		
		2030	2035	2040	2030	2035	2040	2030	2035	2040	2030	2035	2040	2030	2035	2040
BAU	oil	3.5	4.9	6.2	–	–	–	–	–	–	–	–	–	–	–	–
	gas	136.8	191.4	196.4	–	–	–	–	–	–	–	–	–	–	–	–
	coal	147.9	157.9	194.7	–	–	–	–	–	–	–	–	–	–	–	–
	lignite	148.9	76.4	29.4	–	–	–	–	–	–	–	–	–	–	–	–
	nuclear	326.1	315.5	302.8	–	–	–	–	–	–	–	–	–	–	–	–
	biomass	53.1	51.4	50.3	–	–	–	–	–	–	–	–	–	–	–	–
	sum	816.3	797.5	779.8	–	–	–	–	–	–	–	–	–	–	–	–
OFFSH	oil	3.4	4.5	5.8	–	–	–		–	–	–	–	–	–	–	–
	gas	154.2	209.4	210.6	–	–	–	–	–	–	–	–	–	–	–	–
	coal	140.7	157.3	198.8	–	–	–	–	–	–	–	–	–	–	–	–
	lignite	173.3	77.4	25.5	–	–	–	–	–	–	–	–	–	–	–	–
	nuclear	407.5	403.0	398.3	–	–	–	–	–	–	–	–	–	–	–	–
	biomass	71.7	71.4	67.9	–	–	–	–	–	–	–	–	–	–	–	–
	sum	950.8	923.0	906.9	–	–	–	–	–	–	–	–	–	–	–	–
COMBI	oil	3.3	4.4	5.7	3.4	4.5	5.9	3.3	4.3	5.5	3.3	4.9	5.1	2.4	3.4	4.7
	gas	156.6	212.7	214.1	141.3	201.2	206.9	413.4	242.7	228.7	217.2	239.2	235.4	139.3	194.4	194.3
	coal	140.6	157.4	198.9	145.7	159.4	197.8	231.5	156.8	201.1	179.4	182.2	176.5	126.3	142.4	186.8
	lignite	174.5	77.6	25.5	160.8	77.6	27.0	216.4	76.4	22.7	53.8	17.2	15.4	172.9	75.9	22.3
	nuclear	410.8	407.5	403.7	406.2	403.5	398.9	412.7	411.2	407.3	408.6	403.6	396.0	412.2	408.6	404.4
	biomass	71.8	71.5	68.5	70.7	67.5	66.8	72.0	71.9	71.3	71.6	70.1	66.6	71.9	71.4	71.0
	sum	957.6	931.1	916.4	928.1	913.7	903.3	1349.3	963.3	936.6	933.9	917.2	895.0	925.0	896.1	883.5
STAKE	oil	3.3	4.5	5.7	3.4	4.5	5.9	3.3	4.3	5.5	3.3	4.9	5.1	2.4	3.4	4.7
	gas	156.5	212.7	214.1	141.3	201.2	206.9	413.5	242.7	228.7	217.3	239.2	235.4	139.3	194.4	194.4
	coal	140.6	157.5	199.0	145.7	159.3	197.8	231.7	156.9	201.2	179.6	182.2	176.5	126.2	142.5	186.9
	lignite	174.7	77.5	25.5	160.9	77.8	27.0	216.2	76.3	22.7	53.6	17.2	15.4	172.9	75.9	22.3
	nuclear	410.8	407.5	403.7	406.2	403.5	398.9	412.7	411.2	407.3	408.6	403.6	396	412.2	408.6	404.4
	biomass	71.8	71.5	68.5	70.7	67.5	66.8	72.0	71.9	71.3	71.6	70.2	66.6	71.9	71.4	71.0
	sum	957.7	931.2	916.5	928.2	913.8	903.3	1349.4	963.3	936.7	934.0	917.3	895.0	924.9	896.2	883.7

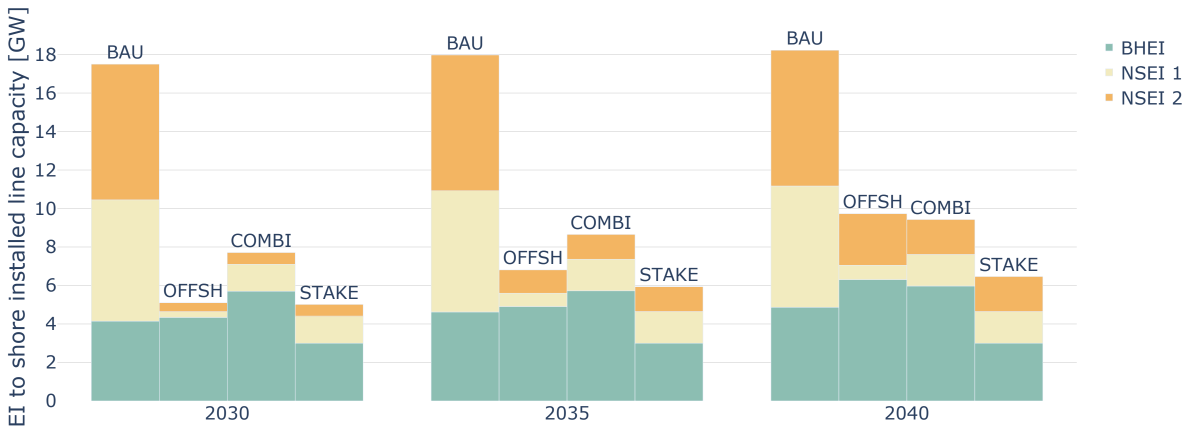


Figure B.8. Aggregated line capacity in the different cases.

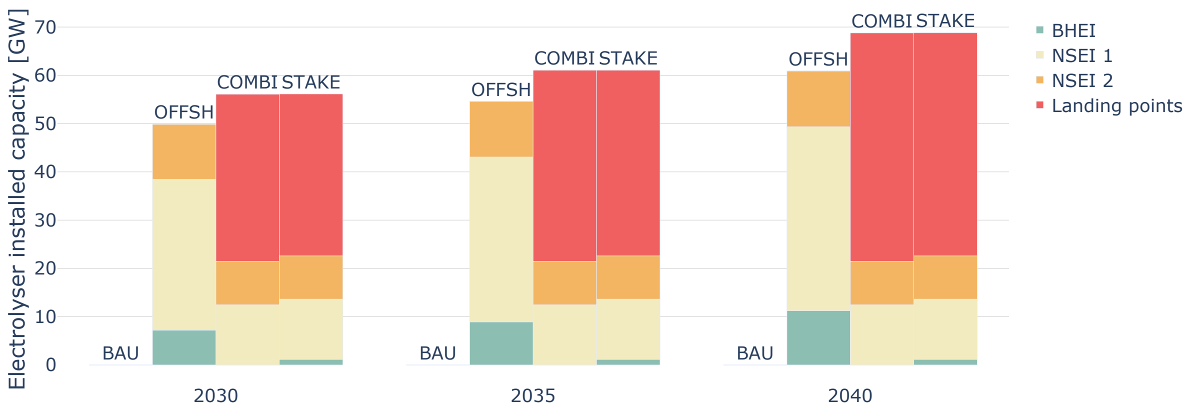


Figure B.9. Aggregated electrolyser capacity in the different cases.

Paper C

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Electrolysis as a Flexibility Resource on Energy Islands

The Case of the North Sea

Article submitted to Energy Policy.

CHAPTER C

Electrolysis as a Flexibility Resource on Energy Islands

C.1 Introduction

With a rising share of intermittent renewable energy sources in electricity systems, the need for operational flexibility is increasing. At the same time, there is a growing demand for low-carbon fuels in sectors where electrification is expensive or infeasible. Electrolysis based on green electricity is envisioned as a solution to both problems.

Electricity production from offshore wind in the North and Baltic Seas has developed rapidly in recent years (Wind Europe, 2021) due to its high potential and social acceptance (Kaldellis et al., 2016). The European Commission's strategy for offshore wind further highlights its importance for the future energy system (European Commission, 2020). Despite technological advances and declining costs of power transmission, transferring electricity from offshore wind farms via sub-sea cables remains costly (IRENA, 2019). One way to reduce the cables required is to convert part of the generated electricity into hydrogen and then transport it to shore via less costly hydrogen pipelines (Singlitico et al., 2021). This idea has been incorporated into the discussions of energy islands (Tosatto et al., 2022). The Danish government and various industrial consortia are now investigating options for integrating hydrogen production from electrolysis with electricity generated at offshore wind farms on potential energy islands.[1]

In our analysis, we assume that the energy islands that are currently under consideration for the North and Baltic Seas will be built and will host electrolysers. We then investigate two possible drivers: flexibility and

[1]For example, see North Sea Wind Power Hub (www.northseawindpowerhub.eu) and the Danish Islands (www.windisland.dk or www.northseaenergyisland.dk/).

profitability. The proximity of the electrolysers to large-scale intermittent wind power generation and the significant distances to load centres and flexibility resources suggests that offshore electrolysers will act as operational flexibility providers in addition to producing cheap hydrogen. In the broader energy system, energy islands could also constitute their own bidding zones in the pan-European electricity market instead of being integrated into existing zones. We summarise our research interests in the following two research questions: (1) What is the flexibility potential of an electrolyser on an energy island? (2) How does the offshore bidding zone configuration influence the value of offshore electrolysers?

To answer these questions, we assess operational patterns, market results, and prices in a setting that incorporates uncertainty in electricity production from renewable energy sources. We do this by developing a two-stage stochastic optimisation model that solves the day-ahead and balancing electricity market clearing problems simultaneously for bidding zones connected by net transfer capacities. Flexibility in our balancing market stage relates to adjustments prior to calling frequency containment reserve and other reserves. Joint market clearing of day-ahead and balancing markets does not happen in today's market operations, so our setup presents an ideal benchmark, likely overestimating the effects. Market power, strategic bidding, and network constraints in bidding zones are not taken into account.

We apply the model to the case of the energy islands in the North and Baltic Seas to answer our research questions for the European context. Our case study includes the projects currently planned by the North Sea Wind Power Hub consortium, the Danish Energy Island (DEI), and the one at Bornholm (Denmark) with their planned wind energy and cable connection capacities and integrates them into the European energy market zones.

For the year 2030, under a moderate renewable expansion scenario, we find that electrolysers do not in general provide significant balancing flexibility, and that offshore electrolysers do not produce large amounts of hydrogen overall. However, offshore bidding zones do make offshore hydrogen production financially more attractive. For the 2040 analysis, we find that the reduction in hydrogen prices outweighs the reduction in electricity cost. This leads to overall lower average run times for the electrolysers (defined as lower *capacity factors*) and reduces their profitability on energy islands. Despite using a specific case in Northern Europe, we make generic assumptions that are applicable to other potential energy islands. For sites with a restricted interconnection capacity to shore and close to large offshore generation facilities, we expect similar patterns.

The remainder of the paper is structured as follows. Section C.2 summarises the literature and background of analysis. In Section C.3, we present the modelling framework. The case study, including data and assumptions, follows in Section C.4, and then the results are given in Section C.5. We discuss the economic viability of electrolysers on energy islands and the impact of our assumptions, and we provide a sensitivity analysis in Section C.6. We present our conclusions and policy recommendations in Section C.7.

C.2 Background and Literature Review

Scientific literature on energy islands is still scarce. In the following, we collect studies of offshore grids and power link islands, the systemic foundations for energy islands, and summarise the few studies on offshore electrolysis and market design for large-scale offshore wind power hubs.

The concept of energy islands emerged around 2016 and was at first driven by the North Sea Wind Power Hub (NSWPH) consortium, which was planning to build an energy island in the North Sea on the Dogger Bank (North Sea Wind Power Hub, 2020). In June 2020, the concept was taken to Danish waters when the government of Denmark decided to build two energy islands, one in the North Sea and one in the Baltic.[2] In consequence, other countries started discussing the feasibility of energy islands, for example, Norway (Zhang et al., 2022) and Germany.[3] All of these ideas are based on the heavy expansion of offshore wind power, which the European Commission envisions as a key part of the energy system transformation (European Commission, 2020).

When power production from offshore wind energy is expanded, the infrastructure in the sea must be expanded simultaneously. One potential way to connect large-scale offshore wind to shore is via integrated

[2]See Klimaaftale by the Danish government (2020): https://fm.dk/media/18085/klimaaftale-for-energi-og-industri-mv-2020.pdf.

[3]See AquaVentus: www.aquaventus.org.

offshore grids (Strbac et al., 2014; Trötscher & Korpås, 2011). These are potentially meshed grid structures in the sea connecting countries through wind farms. They support offshore energy access at several levels (Gea-Bermudez et al., 2018), enable better interconnection to stabilise a renewable energy based system (Schlachtberger et al., 2017), and increase overall welfare through greater and more efficient use of renewable energy (Egerer et al., 2013). Furthermore, offshore grids can connect markets with asymmetric renewable power capacities, which can stabilise prices in those markets (Alavirad et al., 2021). No offshore grids have been commissioned yet, as guidance on design and topology is needed to construct a technically efficient system (Chen et al., 2018), and the economic framework must define operational and ownership rules to incentivise efficient development (Meeus, 2015; Sunila et al., 2019). As an integrating element of offshore grids, Kristiansen et al. (2018) describe power link islands as an efficient component of offshore grids. Power link islands can be seen as the precursor to energy islands, or offshore energy hubs[4], which are generally defined by their offshore location, large surrounding wind capacities, cable connections to land, and possibly storage and conversion technologies (Lüth, 2022). In general, energy hubs are places where multiple energy carriers are converted or stored (Geidl et al., 2007). In light of discussions of a hydrogen economy, electrolysis or power-to-x might act as a conversion technology offshore, and adding power-to-x to a power link island would turn it into an energy island (Gea-Bermúdez et al., 2022). Figure C.1 illustrates how renewable electricity produced locally or nearby can be stored or converted on an energy island.

The concept of energy islands is still at an early stage of development. Some industrial actors have discussed offshore sector integration, including hydrogen production at sea, whereas techno-economic studies find either that the potential for electrolysis offshore is small (Gea Bermúdez et al., 2021; Gea-Bermúdez et al., 2022) or that it relies on the benefit of avoiding the cost of power cable connections (Singlitico et al., 2021). If electrolysers are placed offshore despite the higher capital and operational costs and the uncertainty in regulatory frameworks, it would be best to place them at a centralised location, such as a hub instead of spreading them out (Ibrahim et al., 2022; Singlitico et al., 2021).

[4]In this paper, we use *energy islands*, but the terms can be used interchangeably.

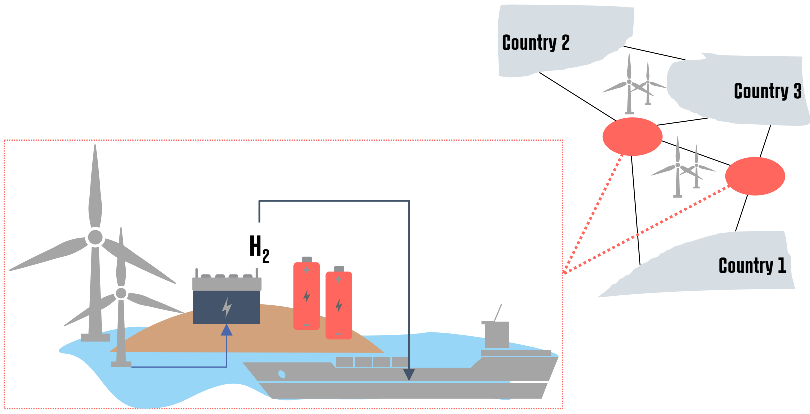
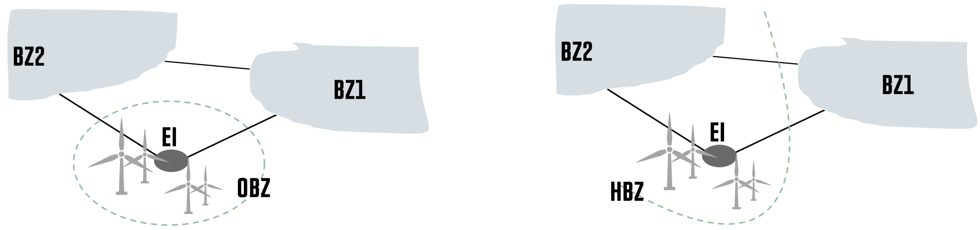


Figure C.1. Sketch of an energy island in the most recent visions.
Source: Authors' illustration.

Research on the technical feasibility of flexible electrolyser operation has also found that temperature and power consumption influence the efficiency and availability of electrolysers for flexibility provision and system services (Qi et al., 2021; Zheng et al., 2022a, 2022b). They further show that electrolysers are technically capable of quickly adjusting their power output in response to fluctuations in renewable power supply. The authors present models and tools for incorporating technical characteristics and temperature dependencies for planning investments and operational strategies regarding electrolysers.

In general, coupling wind farms and hydrogen production increases the cost efficiency and competitiveness of wind power (Grüger et al., 2019; Thommessen et al., 2021). This is tightly linked to our research questions about the profitability and operations of electrolysers on energy islands. In this analysis, we focus on market outcomes and price impacts in an offshore setting. For the onshore case, studies show that power-to-gas in connection with re-electrification can be a viable operating strategy (Grueger et al., 2017), stabilise market prices (Li & Mulder, 2021), and aid congestion management (Xiong et al., 2021). The effect of hydrogen production on flexibility and market prices offshore has not been thoroughly investigated yet.

Several studies have looked into market design and bidding zone configurations for offshore wind energy hubs without electrolysis. These studies usually compare two concepts: offshore bidding zone (OBZ) and home bidding zone (HBZ). In an OBZ, the power hub constitutes its own bidding zone; see Figure C.2(a). Consequently, its market price always matches that of the connected bidding zone with the lowest price. An HBZ (see Figure C.2(b)) represents the business-as-usual case in which wind farms sell electricity in their home markets (Kitzing & Garzón González, 2020; Tosatto et al., 2022). The studies suggest that offshore bidding zones reflect a more efficient electricity market (Kitzing & Garzón González, 2020), but that the distribution of benefits and costs is asymmetrical among the connected actors (Tosatto et al., 2022).



(a) Offshore bidding zone (OBZ) configuration.

(b) Home bidding zone (HBZ) configuration.

Figure C.2. Two bidding zone configurations for offshore wind power hubs and energy islands. In an OBZ, an energy island constitutes its own bidding zone. In an HBZ, the energy island participates in BZ2.

The idea of an offshore bidding zone for power hubs was developed in the context of so-called hybrid projects, in which interconnectors between countries are also connected to wind farms; for example, Kriegers Flak (Marten et al., 2018) which has been operational since 2020. Hybrid projects are fairly new to the system, but in a report for the European Commission, Weichenhain et al. (2019) identify multiple locations where these could be more beneficial than traditional radial connections to the owners' home markets only. In this paper, we make use of the insight that a more cost-reflective offshore bidding zone is preferable and analyse the impact of bidding zone configurations on the operations of offshore electrolysers.

C.3 The Model

We develop a two-stage stochastic optimisation model to analyse the operation and potential of offshore electrolysers as flexibility resource from a systems point of view. The model is based on methods described by Morales et al. (2014) and Conejo et al. (2010). It allows us to observe market prices and quantities sold on the electricity market in the presence of uncertainty in production from renewable energy.

Using the model, we can analyse the value of electrolysers for hydrogen production, functioning as flexible demands, elastic to the price. All power-producing units sell electricity into, and electrolysers demand electricity from, a day-ahead market, the first trading stage of the model. In addition, the units decide whether to bid into a balancing market, the second stage, which is used to compensate for deviations from the day-ahead schedule of renewable power plants. Note that this market is an aggregated and idealised representation of all trading actions between the day-ahead market and the reserve market. This implies that balancing excludes primary, secondary and tertiary reserves and thereby differs from the approach of Energinet (2022). We assume that hydrogen can be sold at any time and volume for a given price without storage or transportation constraints. The capacity of electrolysers is exogenous. To keep the main text succinct, because large parts of the model are quite standard in the power systems literature, we do not include the mathematical formulation here. We explain the structure, objective, and restrictions briefly, and we present and explain the full mathematical model, including constraints and limitations, in Appendix C.7. Figure C.3 summarises the model.

min Generation costs (day-ahead + balancing market)
- profits from hydrogen sales

s.t. Zonal power balance for each stage
Generator capacity limits
Storage limits
Ramp limits
Electrolyser production limits
Net-transfer capacity limits

Figure C.3. Schematic overview of our model. The equations can be found in Appendix C.7.

The objective function of the model minimises the expected costs of day-ahead dispatch and balancing actions under uncertainty. The uncertainty in the model stems from renewable energy production. In our day-ahead dispatch, generators have only a forecast of available renewable power production. In the balancing stage, a set of scenarios represents potential realisations of production. In the first stage, conventional power production and hydrogen production incur costs. In the second stage, the expected costs of balancing originate from conventional power plants adjusting their operational schedules in reaction to deviations in renewable energy production from the forecast. The model has five groups of constraints limiting the solution space. Both stages have a supply-demand balance to ensure that production equals demand. We add a set of capacity restrictions for conventional and renewable energy technology to limit maximum production to installed capacity. For storage (battery and hydropower), we introduce charging and discharging restrictions and a maximum storage level. To avoid an overestimation of operational flexibility, we include ramping constraints for all conventional power plants. Finally, we add more detail on the electrolysers to restrict their maximum production levels and account for efficiency in production.

C.4 The Case of the North Sea

Our model is suitable for analysing energy islands in any geographical region. It replicates market zones and transfer capacities between them for a day-ahead and balancing stage considering uncertainty in renewable energy production. Although the model framework is generic, we focus on the North and the Baltic Seas and the planned energy islands off the coast of Denmark and the Netherlands. Figure C.4 provides an overview of the islands we include in our analysis. DEI and Bornholm are projects led by Danish partners. The North Sea Wind Power Hub involves Danish, Dutch, and German partners and is a Project of Common Interest.[5] In the following two sections, we describe our input data and main assumptions.

C.4.1 Data

We include the 13 countries around the North Sea and the Baltic Sea, which comprise 24 bidding zones in total (see Figure C.13 in the Ap-

[5]See the annex to C(2021) 8409 final by the European Commission: SWD(2021) 335 final.

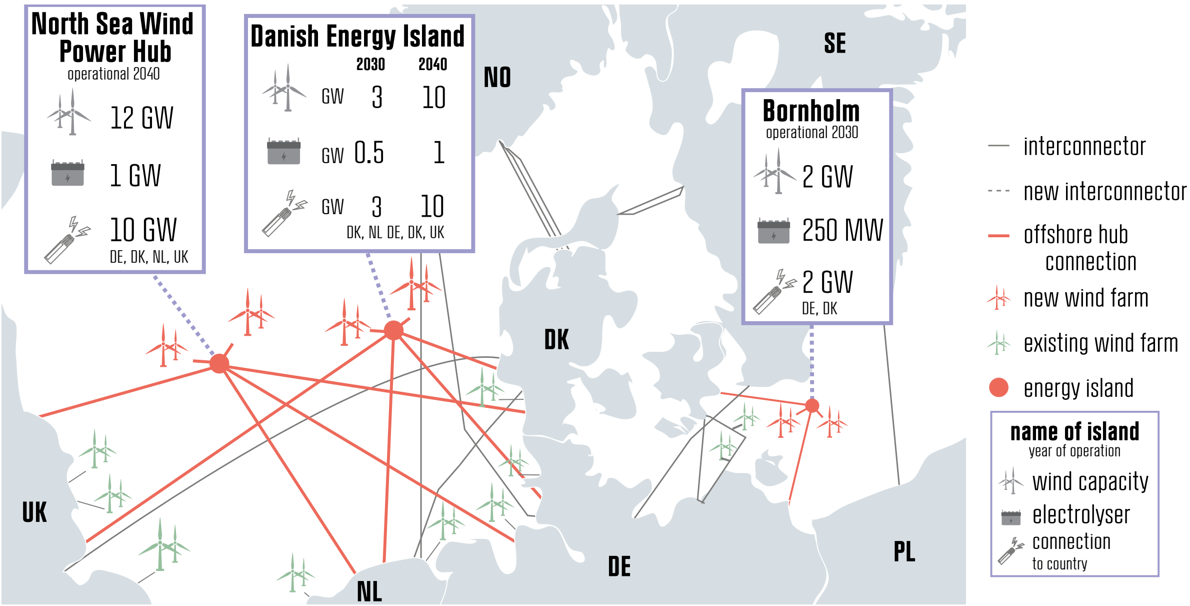


Figure C.4. Energy island projects considered in this study.
Source: Authors' illustration based on COWI (2021) for Energistyrelsen.

pendix). Energy islands are planned to be operational at full capacity in 2040. The first milestones in wind power capacity and interconnection will be reached in 2030. We consider both years in separate analyses.

For each country, we retrieve estimated future capacities for conventional and renewable power plants from the TYNDP 2020 *National Trends* scenario.[6] To compare and crosscheck values, we made use of the ENTSO-E Transparency Platform, and the national system operators' websites, and data published by Kendziorski et al. (2020). For a sensitivity analysis, we use the 1.5 °C scenario *Directed Transition* developed in the openEntrance project[7] as our climate case. It shows significantly higher renewable capacities in Europe—about twice the TYNDP2020 projections (see Figure C.12 in the Appendix).

Generation from renewable energy sources is subject to fluctuations and therefore not available at full capacity in all time steps. We use historical generation profiles for wind and solar energy, which were retrieved from renewables.ninja[8] for the year 2018 (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). Muehlenpfordt (2020) provides spatially and intertemporally correlated day-ahead forecasts and real-time

[6]See TYNDP Data (2020): www.tyndp.entsoe.eu/maps-data/.
[7]See openEntrance (2022): www.openentrance.eu/.
[8]See renewables.ninja (2022): www.renewables.ninja.

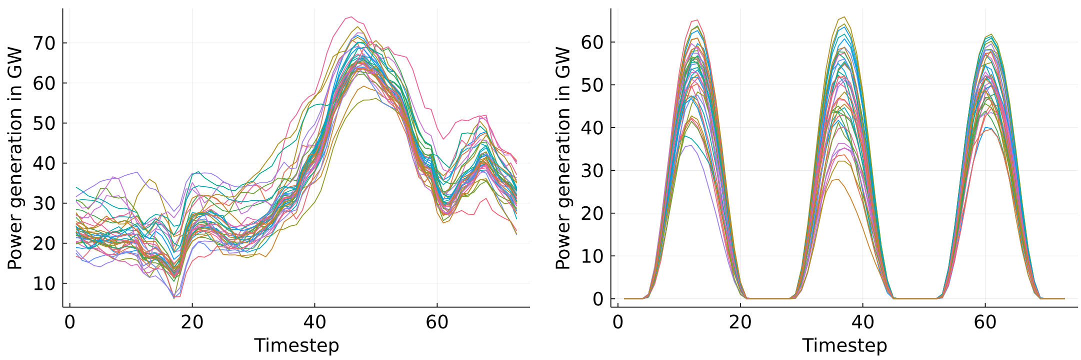
realisations which we use to calculate hourly forecast errors for wind and solar power in each country for the years 1980–2019. After dropping the information about the underlying year, we can generate 40 scenarios, each containing renewable power generation forecast errors for all technologies and countries considered over 8760 hours. We apply those forecast errors to the historical generation profiles from 2018 to produce our second-stage scenarios. The probabilistic power production forecast from onshore wind and solar energy for Germany for a selected time period is shown in Figure C.5.

For reservoir hydro power, we derive a limit for the maximum cumulative production during the selected time of a year from historical production data published on the ENTSO-E Transparency Platform.[9] Run-of-river hydro power operates on the basis of historical availability from the EMPIRE model[10] (Backe et al., 2022). We restrict technologies' ramping capability on the basis of the technology catalogue by the Danish Energy Agency (2022) and historically observed ramping rates for the aggregated power plant portfolio of each fuel type from ENTSO-E's Transparency Platform.

Electricity demand is expected to increase in the coming years towards 2050. We use demand projections from the *National Trends* scenario of the TYNDP 2020 input data. In the process of developing the TYNDP,

[9]See: www.transparency.entsoe.eu/.

[10]OpenEMPIRE is available on GitHub: https://github.com/ntnuiotenergy/OpenEMPIRE.



(a) Onshore Wind **(b)** Solar energy

Figure C.5. Probabilistic power generation forecast from wind and solar power in Germany for a selected time period. Each of the 40 lines corresponds to an individual scenario.

the ENTSOs also gathered data on current net-transfer capacity (NTC) and established projections. We use their projections for 2030 and 2040 as our power exchange capacities between zones in the respective years.

Cost assumptions are a significant driver in an energy system model. Conventional energy technologies have three cost components in our model: marginal production costs, fuel costs, and emission costs. Marginal production costs for conventional power plants can be found in the technology catalogue by the Danish Energy Agency (2022). We use fuel prices for gas, oil, lignite, and hard coal from the TYNDP 2018 input data.[11] For the base case, we adopt the CO_2 price from the same input data, using €84.3/ton in 2030 and €126/ton in 2040. Our ambitious climate case has a price of €350/ton in 2030 and €700/ton in 2040, based on the *Directed Transition* scenario of the openENTRANCE project (Auer et al., 2020).

Another significant economic component in our model is income from selling hydrogen. Costs for hydrogen production from renewable energy depend on the cost of electricity and the investment cost of the electrolyser. Investment costs for alkaline electrolysers are estimated to decrease from €750/kW in 2020 to €350/kW in 2050 (Danish Energy Agency, 2022), and variable operations and maintenance (VOM) costs range between €7.2/MWh in 2030 and €5.6/MWh in 2040 onshore. We assume that offshore VOM costs are 50% higher, with €10.8/MWh in 2030 and €8.4/MWh in 2040. For hydrogen prices, Glenk and Reichelstein (2019) estimate €3.23/kg for 2025 and €2.50/kg for 2040. For production from dedicated wind farms, Meier (2014) estimates hydrogen production costs of €5.2/kg. In later years, assuming existing oil and gas platforms can be reused as bases for renewable offshore hydrogen production, this is projected to decline to €2.50/kg. We use a value of €4.5/kg in 2030 and €3/kg in 2040, which translate to €150/MWh and €100/MWh respectively.

All our data and the model itself are available on GitHub.[12] The model is implemented in Julia 1.6.1 (Bezanson et al., 2017) using JuMP v1.0.0 (Dunning et al., 2017), and solved with Gurobi v9.5.1.

[11]See ENTSO-E map (2022): www.tyndp.entsoe.eu/maps-data.

[12]Find the model here: https://github.com/yannickwerner/EnergyIslands.

Table C.1. Parameter values in the model.

Parameter	Notation	Unit	2030	2040	Source
Fuel prices					
Lignite		€/MWh	8.28	8.28	EUCO: REF 2020 Technology
Hard coal		€/MWh	15.48	15.48	EUCO: REF 2020 Technology
Natural gas		€/MWh	28.84	35.28	EUCO: REF 2020 Technology
Heavy oil		€/MWh	52.56	72.00	EUCO: REF 2020 Technology
Light oil		€/MWh	73.80	87.84	EUCO: REF 2020 Technology
Biomass		€/MWh	11.88	14.40	EUCO: REF 2020 Technology
Uranium		€/MWh	1.69	1.69	EUCO: REF 2020 Technology
CO_2 price		€/ton	84.3	126	TYNDP 2020
Electrolyser cost					
VOM onshore	$mc_{e,y}$	€/MWh	7.2	5.6	Danish Energy Agency (2022)
VOM offshore	$mc_{e,y}$	€/MWh	10.8	8.4	Danish Energy Agency (2022)
Electrolyzer efficiency	η_e		66%	66%	Danish Energy Agency (2022)
Hydrogen price	p^{H_2}	€/MWh	150	100	Glenk and Reichelstein (2019)
Onshore electrolyser capacity					
Denmark		MW	3473.4	4681.7	Klima-, Energi-og Forsyningsministeriet (2021)
The Netherlands		MW	3000	6000*	Government of the Netherlands (2020)
Germany		MW	5000	10000	BMWi (2020)
Belgium		MW	500	500	FPS Economy Belgium (2021)
United Kingdom		MW	5000	8000*	HM Government (2020)
Poland		MW	2000	4000	Ministry of Climate and Environment (2021)
Sweden		MW	5000	10000*	Energimyndiheten (2021)
Norway		MW	750	1500*	NVE (2021)
France		MW	6500	13000	BDI (2020)

* Value extrapolated for 2040 on the basis of estimates given in the sources.

C.4.2 Model Assumptions

We assume that an electrolyser with an exogenously defined size of 0.5 GW (1 GW) and 0.25 GW (0.5 GW) will be placed at DEI and Bornholm respectively, in 2030 (2040); see Figure C.4. The electrolyser on the NSWPH is assumed to be installed with a capacity of 1 GW in 2040. Furthermore, hydrogen can be sold at a fixed price without quantity restrictions. Costs for transport, storage, and distribution of hydrogen are not taken into account explicitly, irrespective of the electrolyser's location. However, we assume that operational and maintenance costs for the offshore electrolyser are 50% higher than onshore (as given in Table C.1) to account for these factors, and for space restrictions, environmental conditions, and the distance to shore. We further assume that all electrolysers that are not built on energy islands are built onshore.

Furthermore, losses on power cables and transmission lines are neglected inside as well as between bidding zones. We consider inflexible, price-inelastic demand for electricity. Demand-side management is not considered in the current state of the model. Unit commitment and minimum power generation restrictions are generally not included in the model. However, we do include a time-varying minimum load for combined heat and power plants based on heat-delivery obligations. We approximate this minimum load by using residential heat demand data from 2013 (Ruhnau et al., 2019; Ruhnau & Muessel, 2022) and increase it by 30 percentage points to account for households that are not connected to district heating grids. Market power, strategic bidding, and network constraints within bidding zones are therefore not taken into account.

It is not possible to run the model for the whole time horizon with a large number of scenarios. To test robustness, we have executed model runs for various numbers of scenarios on a reduced time horizon. We found that neither the balancing service provision nor the capacity factors of the electrolysers change significantly when the number of scenarios is increased beyond ten. Therefore, we use only ten out of forty randomly selected scenarios in order to be able to run the model for longer time horizons. We consider the same probability for each of the ten selected scenarios in our optimisation model.

Due to the computational complexity of the model, we need to split up the full-time horizon of 8760 hours into six segments of equal length (1460 hours). To avoid depletion of pumped hydro and battery storage at the end of each segment, we force the initial and final storage levels to be exactly 50% of the storage capacities.

C.5 Results

We run the model with the described data for the years 2030 and 2040. Our two research questions ask about (1) the flexibility potential of an electrolyser on an energy island, and (2) how bidding zone configuration affects the value of the offshore electrolyser. Following these, we structure the presentation of the results in two parts: Section C.5.1, on flexibility and Section C.5.2 on bidding zones and market analysis. We discuss the results and the shortcomings of the model in Section C.6.

C.5.1 Flexibility of Offshore Electrolysers

Flexibility is needed in the model to compensate for real-time deviations from the day-ahead schedule of renewable energy sources. The system has a set of flexibility resources available for balancing purposes: conventional power plants, hydro power reservoirs, biomass, storage technologies (battery and pumped hydro storage), and electrolysers. Looking at a period of four days in one of the scenarios, in Figure C.6, we see that hydropower and storage units contribute the most to balancing while the electrolysers' contributions (in red) are marginal.

Taking a more regionally disaggregated perspective, Figure C.7 compares the capacity factors over the whole time horizon for the years 2030 and 2040 for the total electrolyser capacity in each bidding zone. For 2030, we observe that most electrolysers are used only for a few hours in the balancing market. Participation in balancing markets is modest for electrolysers on the energy islands (DEI, NSWPH, Bornholm) and even lower for onshore electrolysers. This is due to the availability of cheaper flexibility resources, such as hydro power and storage units, in most onshore bidding zones. Sweden and Norway have especially cheap dispatchable, renewable power generation in the form of hydro, which re-

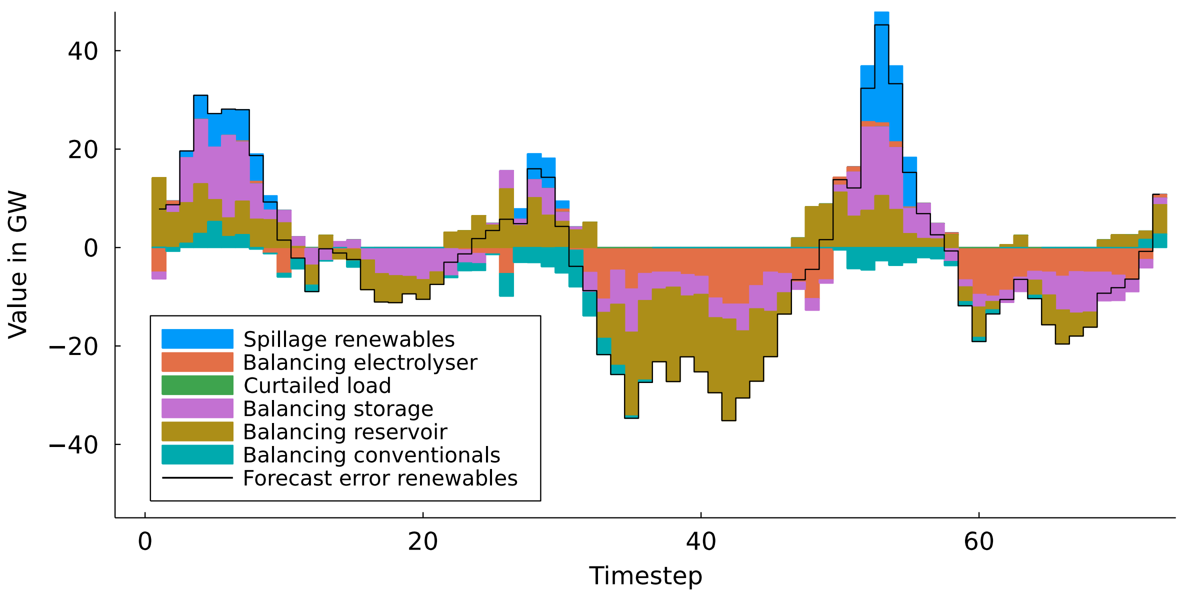


Figure C.6. Balancing of the aggregated system-wide deviation from the day-ahead schedule of renewable power generation in a specific scenario.

sults in low contributions of the electrolysers to the balancing actions in those countries' zones. When we include the day-ahead market, we see that most electrolysers run at rather low capacity factors, below 50% on average and even lower for the offshore electrolysers. Taking a deeper look at the results, we find that hydrogen is produced in fewer hours offshore than onshore, and the average electricity consumption cost per unit of hydrogen produced is much lower for offshore electrolysers. This indicates that it is usually more valuable for the system to transfer electricity to shore and either use it directly or convert it into hydrogen there at lower variable cost, than produce hydrogen offshore.

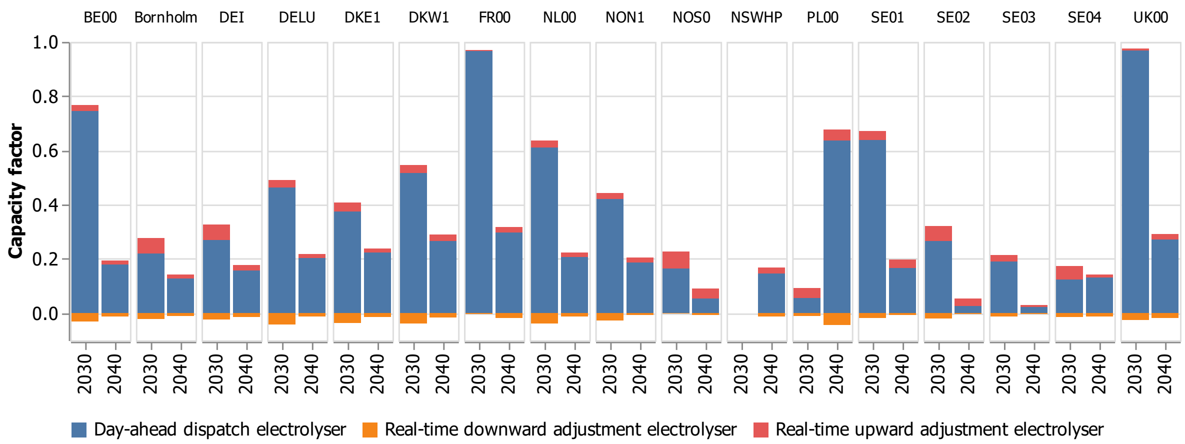


Figure C.7. Expected electrolyser capacity factors for the OBZ configuration in 2030 and 2040. Each bar corresponds to a bidding zone.

Comparing the results for 2030 and 2040, we find that several countries face decreasing capacity factors for their electrolyser fleets despite significantly higher shares of renewable energy capacity in 2040. Although most areas with decreasing capacity factors experience drops in electricity prices, these cannot compensate for the decrease in hydrogen prices and therefore leads to less profitable hydrogen production overall. This is visible in Belgium (zone BE00) and the United Kingdom (zone UK00). One exception is Poland, which experiences high electricity prices in 2030 due to a mostly fossil fuel-based power system but transforms into a renewable-based system with low electricity prices in 2040. We, therefore, see much higher electrolyser capacity factors there, and an increased contribution in the balancing market.

Overall, we find that the expected offshore electrolysers are used in the provision of balancing services for only about 26%-30% of their total run-time. Relatively low capacity factors overall also indicate that operators will face economic challenges to contribute to meeting projected European hydrogen demand in this market setup. Hence, in the next section, we analyse whether an alternative bidding zone configuration would increase the value of offshore electrolysers.

C.5.2 Bidding Zone Configurations

With our second research question, we target the impact of bidding zone configuration on the capacity factors and flexibility contributions of electrolysers. We explore whether zonal boundaries change operational patterns for offshore electrolysers, and if so how. Radial connection of offshore wind farms is the traditional approach to integrating offshore energy, and energy islands in their first operational years could be connected similarly to their home countries, leading to a home market approach. Over the years, this might develop into hybrid projects (see Section C.2), or the islands could come to constitute their own bidding zone. In the following, we compare the case of offshore bidding zones to the standard case of home bidding zones to investigate the role of market zones and their impacts both on the market prices in general and on the energy islands' resources.

In the HBZ, we add the wind farm capacity and electrolysers of each of the three energy islands to its owner country's nearest bidding zone. Figure C.8 compares the capacity factors in 2030 for the two configurations. In the HBZ configuration, electrolysers in the DKW1 and DKE1 zones have slightly higher capacity factors than in the OBZ. In the Danish energy islands, DEI and Bornholm, we observe a decrease in offshore electrolyser capacity factors. However, because the onshore electrolyser capacities are much greater than offshore ones, total hydrogen production increases. We identify two reasons. First, electricity generated offshore is transported to shore and used there, and is preferred over costly offshore electrolysis. Second, in high production hours, none of the hub-shore connecting transmission capacity constraints is binding (a consequence of the HBZ configuration), and less offshore generation is curtailed. Although the flexibility provision by the electrolyser on DEI increases, that of the electrolyser on Bornholm decreases. Those changes are less than one per-

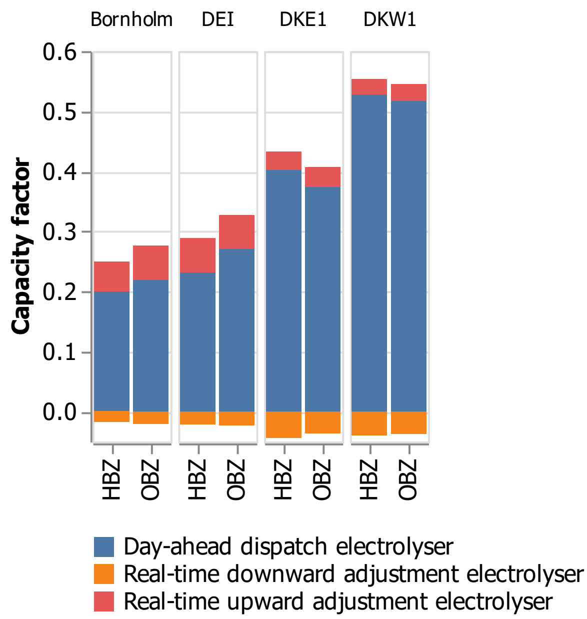
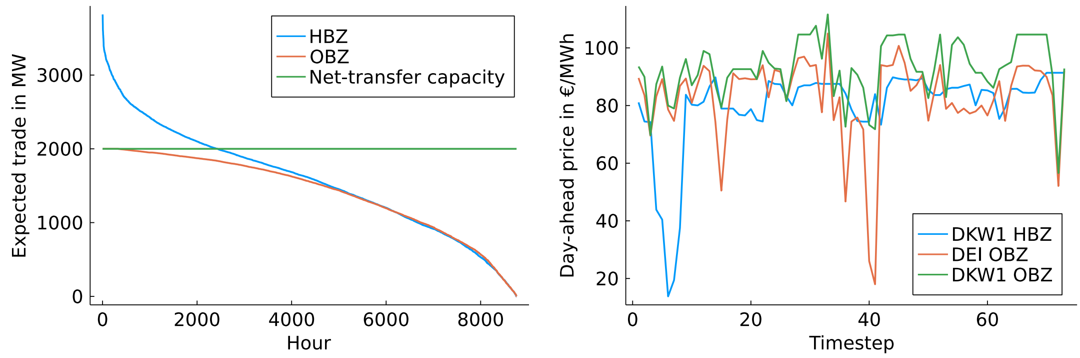


Figure C.8. Expected electrolyser capacity factors for 2030 for the OBZ and HBZ configurations.

centage point and do not affect hydrogen production significantly. Nevertheless, there is no strict tendency in how flexibility provision changes under an HBZ configuration, though it seems to depend on the power plant portfolios of the countries the energy island is connected to.

The differences between the two bidding zone configurations are caused by the way transmission constraints between the energy islands and the mainland are accounted for. Although these constraints impose actual physical limitations in the real operations of the power system, the market itself facilitates a higher electricity exchange between the energy island and its home zone when they are neglected (as in HBZ).

In the following part, we focus on DEI in the North Sea, which is integrated into zone DKW1 (Western Denmark) when the bidding zone configuration is changed. We chose DEI because it is the first island envisioned to be operational by 2030 and it has the most consistent reports and studies available on location, size, and interconnection. Figure C.9(a) illustrates the expected electricity exports from DEI to its home zone of DKW1 in the OBZ and HBZ configurations. The horizontal line shows the projected physical transmission limit of the corresponding interconnector in 2030. In the HBZ case, this limit is expected to be violated in 2429 hours, or about 28% of the time, requiring generally expensive con-



(a) Expected electricity flow from DEI to DKW1 over the whole year.

(b) Expected day-ahead prices during the congested hours only.

Figure C.9. Interconnector flow and prices during congested hours for DEI and zone DKW1.

gestion management. For the OBZ, the interconnector capacity is only binding in 320 hours (4%) over the year, indicating that the dispatch changes drastically when the energy islands become part of an HBZ configuration. These findings also highlight the sensitivity of the system-wide dispatch to the capacity of the interconnectors between the energy islands to shore. In general, the connection from DKW1 to the energy island is barely used for the export of electricity to DEI, where it could be further transported to another connected bidding zone.

Relaxing capacity constraints also affects market prices. Figure C.9(b) shows the power prices on DEI and DKW1 in the OBZ and HBZ configurations when there is congestion in the OBZ case. Note that in an HBZ, DEI is part of DKW1, and thus there is a single day-ahead price. One can see from the graph that electricity prices in the integrated bidding zone fluctuate less than in the OBZ case. Furthermore, the price on DEI in the HBZ configuration (blue) is generally higher than in the OBZ configuration (orange) for the same hours. However, for some hours the price on DEI is much lower in the HBZ configuration. This indicates that the dispatch may be significantly different when the transmission constraint is neglected.

C.6 Discussion

The flexibility and profitability of an electrolyser might work in opposite directions. Although for profitability reasons it is desirable that the electrolysers have high capacity factors, acting as a flexibility resource and participating in the balancing market could be beneficial for the overall system but also reduce their total hydrogen production and eventually their expected profits. In our cases, some flexibility is delivered to the system by the offshore electrolysers, but not as their major service. In general, the capacity factor of offshore installations is lower than that of their onshore counterparts, independently of bidding zone configuration.

From the findings, we identify three points for further investigation: the business case for offshore hydrogen production, discussed in Section C.6.1, the sensitivity of installed capacities and sizing of assets, analysed in Section C.6.2, and finally the model characteristics, reviewed in Section C.6.3.

C.6.1 Business Case

For an offshore hydrogen producer, it is important how much hydrogen can be produced and how expensive the corresponding electricity is. Table C.2 shows hydrogen quantities produced on the energy islands and their expected electricity and marginal[13] costs. With DEI, we observe small differences for the two bidding zone configurations. Despite a slightly higher expected electricity cost in the OBZ, a larger hydrogen

[13]We take into account 20% reduced and increased marginal costs, for upward- and downward-balancing services, respectively.

Table C.2. Operational electrolyser statistics for the year 2030, based on the model results.

Energy island	Configuration	Hydrogen production GWh	Expected marginal cost €/MWh	Expected electricity cost €/MWh	Profit million €
DEI	OBZ	1535.22	12.06	51.79	82.88
DEI	HBZ	1358.11	12.20	48.64	79.57
Bornholm	OBZ	649.64	12.15	46.36	40.24
Bornholm	HBZ	584.85	12.12	46.23	36.41

production leads to a 4% higher expected profit. To evaluate the expected profit of €82.88 million of the electrolyser on DEI in the OBZ configuration, we compare it to the estimated electrolyser investment costs. Based on an investment cost of €0.45 million/MW_{el} in 2030 (Danish Energy Agency, 2022), the annuity for the 0.5 GW electrolyser on DEI is €20.24 million.[14] This indicates that investment in an electrolyser under the assumptions made here might be profitable. Electrolysers onshore face higher expected electricity consumption costs, around €60–€90/MWh. Hence, they need more full-load hours to achieve the same return on investment. Note that we neglect any infrastructure costs for hydrogen transport and assume that hydrogen can be sold at any time and quantity for a price of €150/MWh or €100/MWh in 2030 or 2040, respectively.

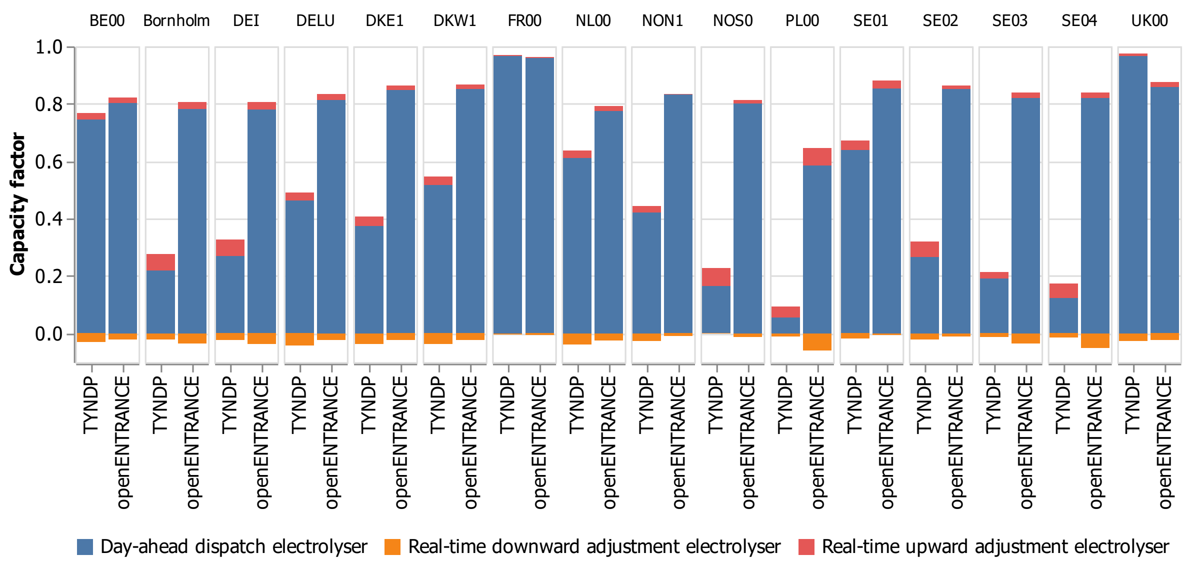


Figure C.10. Expected electrolyser capacity factors for 2030 for the TYNDP and the openENTRANCE data set in the OBZ configuration.

C.6.2 Sensitivity Analyses

The results may be sensitive to two main input parameters: the installed capacities of conventional and renewable energy technologies, and sizes of the assets on and connecting to the energy islands, so we vary these two

[14]We calculate the annuity a on the basis of overnight investment costs I_0 for the year 2030 with an interest rate i of 4% and a lifetime T of 15 years as $a = I_0 \cdot \frac{i \cdot (1+i)^T}{(1+i)^T - 1}$.

parameters. As discussed above, and due to the better representation of the system and the value of scarcity in the OBZ, we perform the sensitivity analysis for the OBZ configuration only.

C.6.2.1 Installed Capacities

The data set from TYNDP 2020 provides a rather conservative outlook on renewable energy capacities in 2030 and 2040. To verify our analyses, we contrast the outcomes with those obtained when using the openENTRANCE project data, which feature much higher capacities (Auer et al., 2020); see Figure C.12 in the Appendix. We refer to this as our *Climate Case*. With significantly higher installed renewable energy capacities but unchanged electrolyser capacities, we observe in Figure C.10 that the electrolyser capacity factors increase to around 90%. There is an increase in hydrogen production on the energy islands, of around 141% (from 1535 GWh to 3691 GWh) on DEI and 183% (from 650 GWh to 1839 GWh) on Bornholm. At the same time, the average expected electricity cost declines by nearly 55% to almost €21/MWh, and the expected profit increases by 350% to €373.34 million on DEI and by 363% to €186.51 million on Bornholm. Hence in a climate-compatible development of the power system with large-scale deployment of additional renewable energy sources, the business case for offshore electrolysers is significantly stronger.

C.6.2.2 Sizing of Electrolysers and Cable Connections

As shown in Figure C.9(a), transfer capacity and line sizing significantly affect hydrogen production. The reference cases originate in industry-led studies of the configuration of energy islands (COWI, 2021; North Sea Wind Power Hub, 2020). To analyse the influence of the chosen interconnector capacities, we consider an increase of 20% and decreases of 20% and 40% in the capacities of the interconnectors connected to the energy islands. The results are shown in Figure C.11 for the OBZ configuration in 2030. Although the capacity factors of the onshore electrolysers in the connected bidding zones decline, those of the electrolysers on the energy islands increase. When interconnector capacities are reduced by 20%, the total capacity factors of the electrolysers on DEI and Bornholm increase by 19.8 and 5.2 percentage points, respectively. Similarly, reducing the interconnector capacity to 60% of its original value increases the total capacity factors by 31.26 and 15.9 percentage points, respectively. In some peak wind production hours, there is not enough interconnector capacity available to balance fluctuations on the energy islands solely by adjusting trade flows. This leads to increased participation in the balancing market by the electrolyser, of around 1 percentage point. Increasing the interconnector capacity so that the total line capacity connected to the energy islands exceeds its wind production capacity does not affect the capacity factors of the electrolyser.

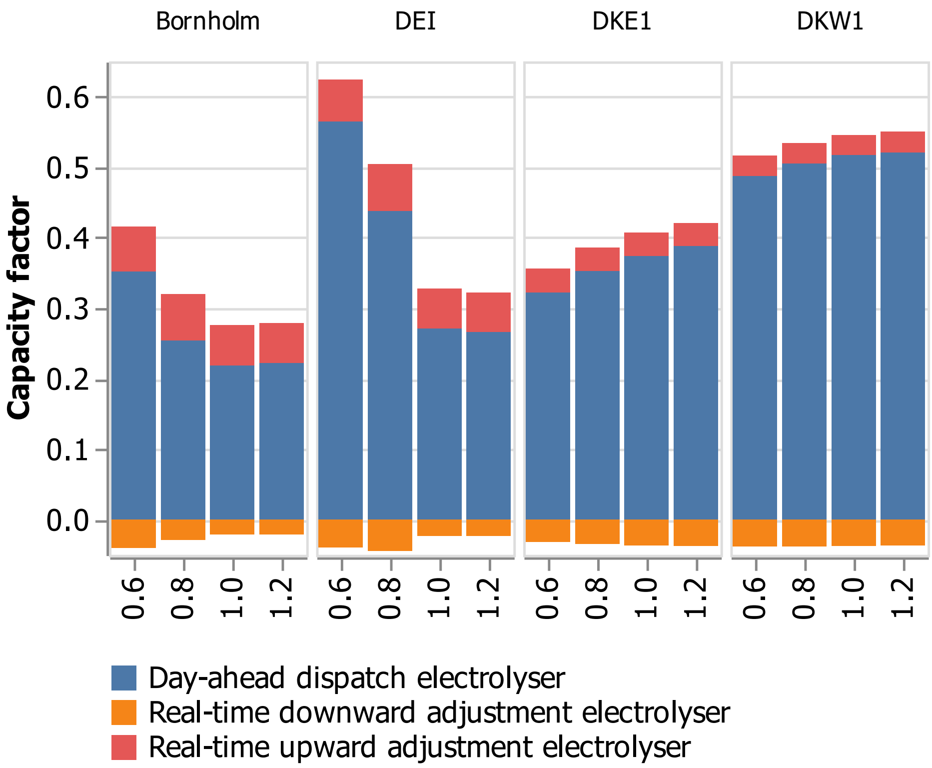


Figure C.11. Electrolyser capacity factors for varying energy island interconnector capacities, adjusted by 20% for OBZ in 2030.

C.6.3 Model Characteristics

Our model follows a frequent approach to analysing stochastic infeed from renewable energy sources in electricity markets. In setting up the model, we make assumptions that affect the results. For instance, to pursue computational tractability, we disregard unit commitment constraints. This means that we neglect any minimum power generation limits, downtimes, necessary minimum run time requirements, and outages, which increases the flexibility of the dispatchable units in the model. To compensate for the risk of having extensively overestimated flexibility from conventional power plants, we include restrictions on the maximum ramp rates based on historical data for 2017 taken from the ENTSO-E Transparency Platform.

We use a net-transfer capacity approach to estimate interconnector capacities. In particular, for cables connecting the energy islands to shore, we assume that their maximum transmission capacity is available at all times. In practice, flow-based market coupling is currently used in Central Western European markets and will likely be adopted across Europe until 2030 (Tosatto et al., 2022). Flow-based market coupling allocates transmission capacities to the interconnectors that have the highest value for the system in the time period considered. Because energy islands host only zero-marginal-cost power production, it is very likely that a flow-based market coupling algorithm will allocate the maximum capacity to the interconnectors connecting those islands to shore. Hence for those interconnectors, flow-based market coupling and the simplified net-transfer capacity scheme adopted here will likely lead to the same outcome. Nevertheless, due to the zonal setup in the model and the net-transfer capacities between the zones, we neglect network constraints within the zones and may overestimate the available grid capacities behind the interconnectors. Refer to Seifert (2022), for instance, who concludes that the national grid plans for 2030 are not yet equipped to accommodate foreseeably large shares of renewable energy and need upward adjustments following national expansion plans.

Lastly, we simulate two market stages only, which do not reflect all stages of the current market frameworks of most European countries. The well-established sequences are the day-ahead market, cleared up to 36 hours before real-time, the intraday market for adjusting to improved forecasts, balancing markets for flexibility, and technical reserves, and for some countries a market-based redispatch or congestion management actions. In this model, we consider a day-ahead market clearing and a real-time balancing adjustment only.

The model's characteristics influence the results to some extent. Whereas using the full net-transfer capacities between countries for trade might be closer to the results of a model with flow-based market coupling, the impact of the reduced technical detail of dispatchable technology overestimates their flexibility potential. For all conventional technologies, reservoir hydropower, and biomass, we include ramp rates but neglect unit commitment and must-run obligations. In addition, for the case of biomass, some regulatory frameworks, for example in Germany and Denmark, incentivise high capacity factors and a price-inflexible operation. Our model allows full adjustment ranges within ramp rates for all technologies, which could lead to an overestimation of the flexibility potential in the system.

C.7 Conclusion and Policy Implications

The concept and implementation of energy islands are driven by several players in governments and industry. The construction of energy islands has not started, and many details are not yet defined. Assuming that those islands will be places for wind energy collection and hydrogen production, we analyse the role of offshore electrolysers.

Our first research question targets the electrolysers' contribution to flexibility. We conclude that flexibility in the system stems mainly from other, cheaper dispatchable sources. Offshore electrolysers do make a modest contribution to balancing services on the energy island, however. Looking at the impact of bidding zone configuration on the operation of the electrolyser, we find that offshore bidding zones lead to slightly higher electrolyser capacity factors and reduced need for congestion management. From our sensitivity analyses, we conclude in summary that (i) significantly higher shares of renewables onshore lead to much higher capacity factors of all electrolysers, but especially of those on the energy islands, and make electrolysers a highly profitable investment, and (ii) reducing the size of the cable connections of energy islands significantly increases the capacity factors of electrolysers and their balancing actions on the islands.

On the basis of our study, we formulate four policy recommendations affecting the role of electrolysers on energy islands:

1. **Flexibility:** Electrolysers can technically react to changes in electricity production and have a broad potential to provide flexibility. But if that potential is to be exploited, economic incentives are needed to make flexibility-oriented operation economically viable. We show that capacity factors are low offshore, and investments in electrolysers as flexibility resources only will need to be supported.

2. **Bidding zone configuration:** Offshore bidding zones reflect the costs and scarcity of energy better than home bidding zones. For electrolysers on energy islands, the OBZ configuration allows higher hydrogen production at lower average electricity costs. This configuration also prevents misalignment between physical network constraints and market solutions, reducing possibly expensive redispatch measures. This suggestion is in line with the conclusions of Kitzing and Garzón González (2020) who consider offshore wind hubs only.

3. **Hydrogen supply:** Discussions of a hydrogen economy are gaining momentum. The European Commission foresees a production of 10 million tonnes in Europe by 2030.[15] If hydrogen is to be produced locally as part of the strategy and is to be prioritised, the costs of electricity for electrolysis should reflect local production costs. Offshore bidding zones can make hydrogen production more viable.

4. **Renewable energy targets:** The renewable energy capacity projections presented in the TYNDP 2020 do not meet renewables targets. Our results indicate that the projected capacities are insufficient to supply the hydrogen needed by low-carbon industry. National and European efforts must therefore incorporate incentives and plans for dedicated and system-based hydrogen production.

This analysis uses a two-stage operational model to analyse the flexibility provision of an offshore electrolyser and the impact of bidding zone configurations on its profitability. The approach can be extended by including unit commitment to obtain a better representation of the operational characteristics of large conventional units. For the representation

[15]See COM(2020) 301 final.

of the electrolyser operation, Flamm et al. (2021) suggest using a mixed integer program for higher accuracy, and Zheng et al. (2022b) highlight the importance of including operational details on temperature dependence and changes of state in the model. Extending the model by adding details of all the technologies could provide further insights. Due to uncertainty in hydrogen demand and prices, further analysis of the impact of both on the viability and on offshore electrolysers will allow a better understanding of how offshore assets can contribute to hydrogen demand and system stability. So far, we have disregarded market power and strategic bidding. However, such bidding might occur around energy islands when operators of wind farms and electrolysers are both aiming for high profits. In particular, ownership structures may influence strategic behaviour. It could be worth analysing the cases of different structures and contracts: Owning and operating wind farms and electrolysers jointly might lead to different market outcomes than when having separate owners and operators. Last, we suggest investigating the impact of current and planned power grids on the role and operation of offshore electrolysers on energy islands. We base our analysis on modelling bidding zones, and we restrict net-transfer capacities. In a follow-up study, examination of flow-based market coupling and inner-zone congestion management will provide further insights.

References

Alavirad, S., Mohammadi, S., Golombok, M., & Haans, K. (2021). Interconnection and generation from a North Sea power hub – A linear electricity model. *International Journal of Electrical Power & Energy Systems*, *133*, 107132. https://doi.org/10.1016/j.ijepes.2021.107132

Auer, H., Crespo del Granado, P., Oei, P.-Y., Hainsch, K., Löffler, K., Burandt, T., Huppmann, D., & Grabaak, I. (2020). Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE. *e & i Elektrotechnik und Informationstechnik*, *137*(7), 346–358. https://doi.org/10.1007/s00502-020-00832-7

Backe, S., Skar, C., del Granado, P. C., Turgut, O., & Tomasgard, A. (2022). EMPIRE: An open-source model based on multi-horizon programming for energy transition analyses. *SoftwareX*, *17*, 100877. https://doi.org/10.1016/j.softx.2021.100877

BDI. (2020). *National strategy for the development of decarbonised and renewable hydrogen in France*. Bretagne Développement Innovation. https://www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-renewable-hydrogen-in-France.pdf

Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM review*, *59*(1), 65–98. https://doi.org/10.1137/141000671

BMWi. (2020). *Die Nationale Wasserstoffstrategie*. Bundesministerium für Wirtschaft und Energie. https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.html

Chen, Q., Rueda Torres, J. L., Tuinema, B. W., & van der Meijden, M. (2018). Comparative Assessment of Topologies for an Offshore Transnational Grid in the North Sea. *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 1–6. https://doi.org/10.1109/ISGTEurope.2018.8571824

Conejo, A. J., Carrión, M., & Morales, J. M. (2010). *Decision Making Under Uncertainty in Electricity Markets* (Vol. 153). Springer US. https://doi.org/10.1007/978-1-4419-7421-1

COWI. (2021). Cost benefit analyse og klimaaftryk af energiøer i Nordsøen og østersøen. https://ens.dk/sites/ens.dk/files/Vindenergi/a209704-001_cost_benefit_analyse_endelig_version.pdf

Danish Energy Agency. (2022). Technology Data for Renewable Fuels. https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf

Dunning, I., Huchette, J., & Lubin, M. (2017). JuMP: A Modeling Language for Mathematical Optimization. *SIAM Review*, *59*(2), 295–320. https://doi.org/10.1137/15M1020575

Egerer, J., Kunz, F., & Hirschhausen, C. v. (2013). Development scenarios for the North and Baltic Seas Grid – A welfare economic analysis. *Utilities Policy*, *27*, 123–134. https://doi.org/10.1016/j.jup.2013.10.002

Energimyndiheten. (2021). Förslag till Sveriges nationella strategi för vätgas, elektrobränslen och ammoniak. https://lighthouse.nu/wp-content/uploads/2021/11/Fo%CC%88rslag-till-nationell-strategi-25-nov.pdf

Energinet. (2022). The Value of Flexibility for Electrolyzers. https://energinet.dk/El/Systemydelser/Nyheder-om-systemydelser/2022-07-01-Flexibility-from-electrolysis

European Commission. (2020). An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future. COM(2020)741/F1. https://ec.europa.eu/transparency/regdoc/rep/1/2020/EN/COM-2020-741-F1-EN-MAIN-PART-1.PDF

Flamm, B., Peter, C., Büchi, F. N., & Lygeros, J. (2021). Electrolyzer modeling and real-time control for optimized production of hydrogen gas. *Applied Energy*, *281*, 116031. https://doi.org/10.1016/j.apenergy.2020.116031

FPS Economy Belgium. (2021). View and strategy Hydrogen. https://economie.fgov.be/sites/default/files/Files/Energy/View-strategy-hydrogen.pdf

Gea Bermúdez, J., Pedersen, R. B. B., Koivisto, M. J., Kitzing, L., & Ramos, A. (2021). *Going offshore or not: Where to generate hydrogen in future integrated energy systems?* (preprint). https://doi.org/10.36227/techrxiv.14806647.v2

Gea-Bermudez, J., Pade, L.-L., Papakonstantinou, A., & Koivisto, M. J. (2018). North Sea Offshore Grid - Effects of Integration Towards 2050. *2018 15th International Conference on the European Energy Market (EEM)*, 1–5. https://doi.org/10.1109/EEM.2018.8469945

Gea-Bermúdez, J., Kitzing, L., Koivisto, M., Das, K., Murcia León, J. P., & Sørensen, P. (2022). The Value of Sector Coupling for the Development of Offshore Power Grids. *Energies*, *15*(3), 747. https://doi.org/10.3390/en15030747

Geidl, M., Koeppel, G., Favre-Perrod, P., Klockl, B., Andersson, G., & Frohlich, K. (2007). Energy hubs for the future. *IEEE Power and Energy Magazine*, *5*(1), 24–30. https://doi.org/10.1109/MPAE.2007.264850

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy*, *4*(3), 216–222. https://doi.org/10.1038/s41560-019-0326-1

Government of the Netherlands. (2020). Government Strategy on Hydrogen. government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen

Grueger, F., Möhrke, F., Robinius, M., & Stolten, D. (2017). Early power to gas applications: Reducing wind farm forecast errors and providing secondary control reserve. *Applied Energy*, *192*, 551–562. https://doi.org/10.1016/j.apenergy.2016.06.131

Grüger, F., Hoch, O., Hartmann, J., Robinius, M., & Stolten, D. (2019). Optimized electrolyzer operation: Employing forecasts of wind energy availability, hydrogen demand, and electricity prices. *International Journal of Hydrogen Energy*, *44*(9), 4387–4397. https://doi.org/10.1016/j.ijhydene.2018.07.165

HM Government. (2020). The Ten Point Plan for a Green Industrial Revolution. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

Ibrahim, O. S., Singlitico, A., Proskovics, R., McDonagh, S., Desmond, C., & Murphy, J. D. (2022). Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies. *Renewable and Sustainable Energy Reviews*, *160*, 112310. https://doi.org/10.1016/j.rser.2022.112310

IRENA. (2019). *Renewable power generation costs in 2018*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

Kaldellis, J., Apostolou, D., Kapsali, M., & Kondili, E. (2016). Environmental and social footprint of offshore wind energy. Comparison with onshore counterpart. *Renewable Energy*, *92*, 543–556. https://doi.org/10.1016/j.renene.2016.02.018

Kendziorski, M., Zozmann, E., & Kunz, F. (2020). National generation capacity. https://doi.org/10.25832/NATIONAL_GENERATION_CAPACITY/2020-10-01

Kitzing, L., & Garzón González, M. (2020). *Market arrangements for offshore wind energy networks*. Danmarks Tekniske Universitet. https://orbit.dtu.dk/en/publications/market-arrangements-for-offshore-wind-energy-networks

Klima-, Energi-og Forsyningsministeriet. (2021). Regeringens Strategi for Power-to-X. https://kefm.dk/Media/637751860733099677/Regeringens%20strategi%20for%20Power-to-X.pdf

Kristiansen, M., Korpås, M., & Farahmand, H. (2018). Towards a fully integrated North Sea offshore grid: An engineering-economic assessment of a power link island. *WIREs Energy and Environment*, *7*(4). https://doi.org/10.1002/wene.296

Li, X., & Mulder, M. (2021). Value of power-to-gas as a flexibility option in integrated electricity and hydrogen markets. *Applied Energy*, *304*, 117863. https://doi.org/10.1016/j.apenergy.2021.117863

Lüth, A. (2022). *Risks, Strategies, and Benefits of Offshore Energy Hubs - A Literature-Based Survey.*

Marten, A.-K., Akmatov, V., Sørensen, T. B., Stornowski, R., Westermann, D., & Brosinsky, C. (2018). Kriegers flak-combined grid solution: Coordinated cross-border control of a meshed HVAC/HVDC offshore wind power grid. *IET Renewable Power Generation*, *12*(13), 1493–1499. https://doi.org/10.1049/iet-rpg.2017.0792

Meeus, L. (2015). Offshore grids for renewables: Do we need a particular regulatory framework? *Economics of Energy & Environmental Policy*, *4*(1). https://doi.org/10.5547/2160-5890.4.1.lmee

Meier, K. (2014). Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: Techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology. *International Journal of Energy and Environmental Engineering*, *5*(2-3), 104. https://doi.org/10.1007/s40095-014-0104-6

Ministry of Climate and Environment. (2021). 2030 Polish Hydrogen Strategy. https://ec.europa.eu/energy/sites/default/files/documents/8_-_polish_hydrogen_strategy_draft_presentation.pdf

Morales, J. M., Conejo, A. J., Madsen, H., Pinson, P., & Zugno, M. (2014). *Integrating Renewables in Electricity Markets* (Vol. 205). Springer US. https://doi.org/10.1007/978-1-4614-9411-9

Muehlenpfordt, J. (2020). Time series. https://doi.org/10.25832/TIME_SERIES/2020-10-06

North Sea Wind Power Hub. (2020). Vision \textbar North Sea Wind Power Hub. https://northseawindpowerhub.eu/vision

NVE. (2021). Langsiktig Kraftmarkedsanalyse 2021 – 2040. https://publikasjoner.nve.no/rapport/2021/rapport2021_29.pdf

Pfenninger, S., & Staffell, I. (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy*, *114*, 1251–1265. https://doi.org/10.1016/j.energy.2016.08.060

Qi, R., Qiu, Y., Lin, J., Song, Y., Li, W., Xing, X., & Hu, Q. (2021). Two-stage stochastic programming-based capacity optimization for a high-temperature electrolysis system considering dynamic operation strategies. *Journal of Energy Storage*, *40*, 102733. https://doi.org/10.1016/j.est.2021.102733

Ruhnau, O., Hirth, L., & Praktiknjo, A. (2019). Time series of heat demand and heat pump efficiency for energy system modeling. *Scientific Data*, *6*(1), 189. https://doi.org/10.1038/s41597-019-0199-y

Ruhnau, O., & Muessel, J. (2022). When2heat. https://doi.org/10.25832/when2heat/2022-02-22

Schlachtberger, D., Brown, T., Schramm, S., & Greiner, M. (2017). The benefits of cooperation in a highly renewable European electricity network. *Energy*, *134*, 469–481. https://doi.org/10.1016/j.energy.2017.06.004

Seifert, P. E. (2022). *The Value of Large-Scale Offshore Distribution Islands: Benefits of Sector Coupling and Multi-Country Connections using the Example of Bornholm Energy Island* (Master's thesis). TU Berlin.

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. *Renewable and Sustainable Energy Transition*, *1*, 100005. https://doi.org/10.1016/j.rset.2021.100005

Staffell, I., & Pfenninger, S. (2016). Using bias-corrected reanalysis to simulate current and future wind power output. *Energy*, *114*, 1224–1239. https://doi.org/10.1016/j.energy.2016.08.068

Strbac, G., Moreno Vieyra, R., Konstantelos, I., Aunedi, M., & Pudjianto, D. (2014). *Strategic Development of North Sea Grid Infrastructure to Facilitate Least-Cost Decarbonisation*. Imperial College London. https://doi.org/10.25561/28452

Sunila, K., Bergaentzlé, C., Martin, B., & Ekroos, A. (2019). A supra-national TSO to enhance offshore wind power development in the Baltic Sea? A legal and regulatory analysis. *Energy Policy*, *128*, 775–782. https://doi.org/10.1016/j.enpol.2019.01.047

Thommessen, C., Otto, M., Nigbur, F., Roes, J., & Heinzel, A. (2021). Techno-economic system analysis of an offshore energy hub with an outlook on electrofuel applications. *Smart Energy*, *3*, 100027. https://doi.org/10.1016/j.segy.2021.100027

Tosatto, A., Beseler, X. M., Østergaard, J., Pinson, P., & Chatzivasileiadis, S. (2022). North Sea Energy Islands: Impact on national markets and grids. *Energy Policy*, *167*, 112907. https://doi.org/10.1016/j.enpol.2022.112907

Trötscher, T., & Korpås, M. (2011). A framework to determine optimal offshore grid structures for wind power integration and power exchange: A framework to determine optimal offshore grid structures. *Wind Energy*, *14*(8), 977–992. https://doi.org/10.1002/we.461

Weichenhain, U., Elsen, S., Zorn, T., Kern, S., & European Commission. (2019). Hybrid projects how to reduce costs and space of offshore developments: North Seas Offshore Energy Clusters study. https://doi.org/10.2833/416539

Wind Europe. (2021). Offshore Wind in Europe. https://proceedings.windeurope.org/biplatform/rails/active_storage/blobs//WindEurope-Offshore-wind-in-Europe-statistics-2020.pdf

Xiong, B., Predel, J., Crespo del Granado, P., & Egging-Bratseth, R. (2021). Spatial flexibility in redispatch: Supporting low carbon energy systems with Power-to-

Gas. *Applied Energy*, *283*, 116201. https://doi.org/10.1016/j.apenergy.2020.116201

Zhang, H., Tomasgard, A., Knudsen, B. R., Svendsen, H. G., Bakker, S. J., & Grossmann, I. E. (2022). Modelling and analysis of offshore energy hubs. *Energy*, *261*, 125219. https://doi.org/10.1016/j.energy.2022.125219

Zheng, Y., You, S., Bindner, H. W., & Münster, M. (2022a). Incorporating optimal operation strategies into investment planning for wind/electrolyser system. *CSEE Journal of Power and Energy Systems*. https://doi.org/10.17775/CSEEJPES.2021.04240

Zheng, Y., You, S., Bindner, H. W., & Münster, M. (2022b). Optimal day-ahead dispatch of an alkaline electrolyser system concerning thermal–electric properties and state-transitional dynamics. *Applied Energy*, *307*, 118091. https://doi.org/10.1016/j.apenergy.2021.118091

Appendix to Paper C

Model Formulation

The following section describes the modelling framework that we paraphrase in Section C.3. The paragraphs explain the mathematical model and its characteristics, and Table C.3 provides the nomenclature. Variables are denoted in capital letters, scalars and parameters in small letters.

Table C.3. Designated sets, parameters, and variables of the mathematical model.

Sets	
$n \in \mathcal{N}$	zone n in set of zones $\mathcal{N}$
$t \in \mathcal{T}$	hour t in time horizon $\mathcal{T}$
$i \in \mathcal{I} \subset \mathcal{U}$	technology i of all conventional technologies $\mathcal{I}$
$j \in \mathcal{J}$	technology j of all renewable plants $\mathcal{J}$
$e \in \mathcal{E}$	electrolyser e of all electrolysers $\mathcal{E}$
$s \in \mathcal{S}$	storage unit s of all storage units
$r \in \mathcal{R} \subset \mathcal{U}$	technology r of all reservoirs
$u \in \mathcal{U} \supset \mathcal{I}, \mathcal{R}$	technology u of all dispatchable technologies for balancing
$d \in \mathcal{D}$	demand d of all demands $\mathcal{D}$
$f \in \mathcal{F}$	line f of all lines $\mathcal{F}$
$\omega \in \Omega$	scenario ω of all scenarios
Parameters	
$g^{\mathrm{tot}}_{\omega,r}$	maximum total production for reservoir r in scenario ω over all t
g^{max}_{u}	maximum generation capacity of unit u
$r^{\mathrm{down/up}}_{u}$	maximum downward/upward ramping capacity of dispatchable unit u
$r^{\mathrm{down/up},G}_{s}$	maximum downward ramping capacity of storage s
$r^{\mathrm{down/up},L}_{s}$	maximum upward ramping capacity of storage s
$g^{\mathrm{real}}_{j,t}$	renewable energy production of unit j in time step t
l^{max}_{e}	maximum consumption of electrolyser e
$l^{\mathrm{el}}_{d,t}$	demand of load d in time step t
$mc_{u/j/e}$	marginal production cost of unit $u/j/e$ per MWh
$p^{\mathrm{H_2}}$	price per kWh hydrogen sold
$p^{\mathrm{up,B}}_{i/e}$	marginal upwards balancing cost of unit i/e per MWh
$p^{\mathrm{down,B}}_{i/e}$	marginal downwards balancing cost of unit i/e per MWh
p^{LOL}	value of lost load per kWh
$ntc_{n,m}$	net transfer capacity on line from n to m
$s^{\mathrm{min}}_{s}/s^{\mathrm{max}}_{s}$	lower/upper storage level of storage s
$\eta^{\mathrm{G/L}}_{s}$	discharge/charge efficiency of storage s
η_{e}	conversion efficiency of electrolyser e
$\pi_{\omega,t}$	probability of occurrence of scenario ω in time step t

Decision Variables

$F_{f,t} \in \mathbb{R}^+$	flow on line f from zone n and m in time step t
$G_{u,t} \in \mathbb{R}^+$	generation by unit u in time step t
$G_{s,t} \in \mathbb{R}^+$	generation by storage s in time step t
$G^S_{j,t} \in \mathbb{R}^+$	scheduled renewable generation from unit j in time step t
$L_{e,t} \in \mathbb{R}^+$	load of electrolyser e in time step t
$L_{s,t} \in \mathbb{R}^+$	load/charge of storage s in time step t
$B^{\text{up}}_{\omega,u/e,t} \in \mathbb{R}^+$	upwards balancing of unit u/e in time step t
$B^{\text{down}}_{\omega,u/e,t} \in \mathbb{R}^+$	downwards balancing of unit u/e in time step t
$B^{\text{up,G}}_{\omega,s,t} \in \mathbb{R}^+$	upwards balancing of discharging storage s in time step t
$B^{\text{down,G}}_{\omega,s,t} \in \mathbb{R}^+$	downwards balancing of discharging storage s in time step t
$B^{\text{up,L}}_{\omega,s,t} \in \mathbb{R}^+$	upwards balancing/reduced consumption of storage s in time step t
$B^{\text{down,L}}_{\omega,s,t} \in \mathbb{R}^+$	downwards balancing/increased consumption of storage s in time step t
$F^{\text{adj}}_{\omega,f,t} \in \mathbb{R}$	adjusted flow on line f from n and m in time step t
$G^{\text{CU}}_{\omega,j,t} \in \mathbb{R}^+$	curtailed renewable energy from unit j in time step t
$L^{\text{shed}}_{\omega,d,t} \in \mathbb{R}^+$	shedded load d in time step t
$S_{\omega,s,t} \in \mathbb{R}^+$	storage level of storage s in time step t
$B^{\text{ramp}}_{u/s,t,\omega} \in \mathbb{R}$	ramping of unit u/s in timestep t and scenario ω

Objective. The objective is to minimise the expected total operational costs for electricity generation adjusted for the profit from hydrogen production for each hour $t \in \mathcal{T}$ in a co-integrated market comprising day-ahead and balancing markets. Let $i \in \mathcal{I},\ j \in \mathcal{J},\ s \in \mathcal{S},\ r \in \mathcal{R},\ e \in \mathcal{E}$ denote the sets of conventional, intermittent renewable, storage, hydro reservoir, and electrolyser technologies, respectively. For simplicity, we aggregate all power plants of the same technology in each country to a single unit so that every country hosts at maximum one power plant of each technology. Furthermore, we assume that all power plants of an individual technology have exactly the same operational characteristics—cost structure, technical constraints, and so forth. All inflexible price-inelastic demands denoted by $d \in \mathcal{D}$ are also treated the same and incur the same load-shedding cost. We introduce scenarios $\omega \in \Omega$ in the second stage to represent different power production levels from renewable energy sources.

Eq. (C.1) minimises the sum of costs for the first-stage decision C^{DA}_t and the costs for the second stage balancing $C^{\text{BA}}_{\omega,t}$. The costs in the second stage are represented by the sum over all scenarios ω weighted by their probability $\pi_{\omega,t}$.

$$\min \sum_{t\in\mathcal{T}} \left[C^{\text{DA}}_t + \sum_{\omega\in\Omega} \left(\pi_{\omega,t} \cdot C^{\text{BA}}_{\omega,t} \right) \right] \tag{C.1}$$

Costs in the first stage include the sum of costs for conventional power production and hydrogen production costs related to the day-ahead schedules; see Eq. (C.2). For the day-ahead market, we account for the marginal cost mc_i for the dispatchable generation $G_{i,t}$ of all conventional generators i. Hydro power reservoirs and storage technologies are assumed to have zero marginal cost. $L_{e,t}$ denotes the power demand of the electrolyser and $\eta_e < 1$ the power-to-hydrogen efficiency of electrolyser e. Term $(\eta_e p^{\mathrm{H_2}} - mc_e)$ denotes the income from producing and selling of hydrogen:

$$C_t^{\mathrm{DA}} = \sum_{i \in \mathcal{I}} (mc_i \cdot G_{i,t}) - \sum_{e \in \mathcal{E}} (\eta_e \cdot p^{\mathrm{H_2}} - mc_e) \cdot L_{e,t}, \qquad \forall\, t \in \mathcal{T} \tag{C.2}$$

Costs in the second stage of the model arise from providing balancing energy in response to system needs in each scenario ω. Eq. (C.3) is thus built similarly to the first-stage costs but adds the costs for upwards and downwards balancing for the available technologies that have non-zero marginal costs of production. For conventional technologies and electrolysers, we include upwards $B^{\mathrm{up}}_{\omega,i,t}$, $B^{\mathrm{up}}_{\omega,e,t}$ and downwards $B^{\mathrm{down}}_{\omega,i,t}$, $B^{\mathrm{down}}_{\omega,e,t}$. For conventional technologies, we assume that upward (downward) balancing costs are 20% above (below) their marginal costs. For electrolysers, we additionally include revenues (losses) for additional (reduced) hydrogen production in the case of downward (upward) balancing service provision. For further explanation of the derivation of the balancing bid prices see Appendix C.7. In real-time operations, it is also possible to shed loads $L^{\mathrm{shed}}_{\omega,d,t}$ at a (sufficiently high) cost p^{LOL} to ensure that this action is taken only when the supply–demand balance cannot be achieved otherwise. Power production from renewable energy sources is assumed to have zero marginal cost and can be curtailed without a penalty.

$$\begin{aligned} C^{\mathrm{BA}}_{\omega,t} = & \sum_{i \in \mathcal{I}} \left(p_i^{\mathrm{up,B}} \cdot B^{\mathrm{up}}_{\omega,i,t} - p_i^{\mathrm{down,B}} \cdot B^{\mathrm{down}}_{\omega,i,t} \right) \\ & + \sum_{e \in \mathcal{E}} \left(p_e^{\mathrm{up,B}} \cdot B^{\mathrm{up}}_{\omega,e,t} - p_e^{\mathrm{down,B}} \cdot B^{\mathrm{down}}_{\omega,e,t} \right) \\ & + \sum_{d \in \mathcal{D}} p^{\mathrm{LOL}} \cdot L^{\mathrm{shed}}_{\omega,d,t}, \qquad \forall\, \omega \in \Omega, t \in \mathcal{T} \end{aligned} \tag{C.3}$$

The decisions on day-ahead and real-time power production are restricted by a set of constraints. We introduce a supply–demand-balance for each stage, ensuring that electricity supply equals demand at all times. For all technologies, the model includes a constraint to limit their maximum power output to their installed capacity and considers ramping limits for the change of power production between time steps. Exchange capacities between the zones are limited to a maximum net-transfer capacity. Storage units have a constraint on maximum storage level and charge and discharge rates. The electrolysers are modelled as power consuming units similar to battery storage in charging mode.

Supply-demand balances. For the first stage, the supply-demand balance given in Eq. (C.4) must hold: in each zone, the generation from dispatchable units $G_{u,t}$, scheduled renewables $G^{\mathrm{S}}_{j,t}$, storage $G_{s,t}$, and trade $F_{f,t}$ (incoming and outgoing) have to equal the demand for loads $l^{\mathrm{el}}_{d,t}$, hydrogen production $L_{e,t}$, and storage charge $L_{s,t}$.

$$\begin{aligned}
&\sum_{u\in\Delta_n^G} G_{u,t} + \sum_{s\in\Delta_n^S} G_{s,t} + \sum_{j\in\Delta_n^J} G^{\mathrm{S}}_{j,t} \\
&- \sum_{d\in\Delta_n^D} l^{\mathrm{el}}_{d,t} - \sum_{e\in\Delta_n^E} L_{e,t} - \sum_{s\in\Delta_n^S} L_{s,t} \\
&- \sum_{f\in\mathcal{F}_n^{out}} F_{f,t} + \sum_{f\in\mathcal{F}_n^{in}} F_{f,t} = 0, \qquad\qquad \forall\, n\in\mathcal{N}, t\in\mathcal{T}
\end{aligned} \tag{C.4}$$

For the second stage, deviations from forecasted values for stochastic generation must be balanced. We introduce uncertainty through scenarios ω in this stage in Eq. (C.5). In this model, deviations of scheduled intermittent production $G^S_{j,t}$ from $g^{\mathrm{real}}_{\omega,j,t}$ are to be balanced by either curtailing renewables $G^{\mathrm{CU}}_{j,t}$, using balancing services of dispatchable technologies u for up- or downwards adjustments $B^{\mathrm{up}}_{\omega,u,t}, B^{\mathrm{down}}_{\omega,u,t}$, increasing or decreasing the output of an electrolyser $B^{\mathrm{up}}_{\omega,e,t}, B^{\mathrm{down}}_{\omega,e,t}$ or storage units $B^{\mathrm{up,L}}_{\omega,s,t}, B^{\mathrm{down,L}}_{\omega,s,t}, B^{\mathrm{up,G}}_{\omega,s,t}, B^{\mathrm{down,G}}_{\omega,s,t}$. Note that we explicitly allow storage units to not only adjust their day-ahead market schedules in the same direction, but to change the operational mode in the balancing stage. For example, if a storage unit is charging in the day-ahead market, we allow it to fully revert this action and additionally discharge in the balancing stage.

Apart from that, net exchange with neighbouring zones $F^{\mathrm{adj}}_{\omega,f,t}$ can be adjusted and load can be shedded $L^{\text{shed}}_{\omega,d,t}$.

$$\begin{aligned}
&\sum_{j\in\Delta^J_n}(g^{\text{real}}_{\omega,j,t} - G^{\text{S}}_{j,t} - G^{\text{CU}}_{\omega,j,t}) \\
&+ \sum_{u\in\Delta^U_n}(B^{\text{U}}_{\omega,u,t} - B^{\text{D}}_{\omega,u,t}) + \sum_{e\in\Delta^E_n}(B^{\text{up}}_{\omega,e,t} - B^{\text{down}}_{\omega,e,t}) \\
&+ \sum_{s\in\Delta^S_n}(B^{\text{up,G}}_{\omega,s,t} + B^{\text{up,L}}_{\omega,s,t} - B^{\text{down,G}}_{\omega,s,t} - B^{\text{down,L}}_{\omega,s,t}) \\
&+ \sum_{d\in\Delta^D_n} L^{\text{shed}}_{\omega,d,t} - \sum_{f\in\mathcal{F}^{out}_n} F^{\text{adj}}_{\omega,f,t} + \sum_{f\in\mathcal{F}^{in}_n} F^{\text{adj}}_{\omega,f,t} = 0, \quad \forall\omega\in\Omega, n\in\mathcal{N}, t\in\mathcal{T}
\end{aligned} \tag{C.5}$$

Capacity constraints for conventional and reservoir units. Generation capacities for all units are limited in size. To represent these limits, we enforce a series of capacity constraints on the model's stages.

For renewable energy, the scheduled energy production $G^S_{j,t}$ cannot exceed its installed capacity $g^{\max}_j$. Curtailment $G^{\text{CU}}_{\omega,j,t}$ in the second stage cannot be larger than the realisation of renewable $g^{\text{real}}_{\omega,j,t}$ production.

$$G^S_{j,t} \le g^{\max}_j \qquad \forall\, j\in J, t\in T \tag{C.6}$$
$$G^{\text{CU}}_{\omega,j,t} \le g^{\text{real}}_{\omega,j,t} \qquad \forall\, \omega\in\Omega, j\in\mathcal{J}, t\in\mathcal{T} \tag{C.7}$$

For conventional technologies, including hydro power reservoirs, generation $G_{u,t}$ including balancing capacity $B^{\text{up}}_{\omega,u,t}$ and $B^{\text{down}}_{\omega,i,t}$ must lie between zero and the maximum installed capacity $g^{\max}_u$, as displayed in Eq. (C.8) and Eq. (C.9).

$$G_{u,t} + B^{\text{up}}_{\omega,u,t} \le g^{\max}_u \qquad \forall\, \omega\in\Omega, u\in\mathcal{U}, t\in\mathcal{T} \tag{C.8}$$
$$G_{u,t} - B^{\text{down}}_{\omega,u,t} \ge 0 \qquad \forall\, \omega\in\Omega, u\in\mathcal{U}, t\in\mathcal{T} \tag{C.9}$$

Reservoir. For generation from water reservoirs, we restrict the sum of generation over the time horizon to a scenario-specific maximum $g^{\text{tot}}_{\omega,r}$.

$$\sum_{t\in\mathcal{T}}(G_{r,t} + B^{\text{up}}_{\omega,r,t} - B^{\text{down}}_{\omega,r,t}) \le g^{\text{tot}}_{\omega,r}, \qquad \forall\, \omega\in\Omega, r\in R \tag{C.10}$$

Combined heat and power plants. Let $c\in\mathcal{I}^c\subseteq\mathcal{I}$ denote the set of combined heat and power (CHP) plants that are often subject to heat delivery contracts and therefore have limited flexibility. We include a time-varying minimum run requirement in our model to reflect this:

$$G_{c,t} - B^{\text{down}}_{\omega,c,t} \geq g_{\text{c},t}, \qquad \forall\, \omega \in \Omega, c \in \mathcal{I}^c, t \in \mathcal{T} \tag{C.11}$$

Exchange constraints and load shedding. In the model, we allow for exchange between different zones $n \in \mathcal{N}$ given a specific line (interconnector) capacity. Let $\mathcal{F}$ denote the set of interconnectors, where interconnector f connects zones $n, m \in \mathcal{N}$. For simplicity, we use $f = (n, m)$ interchangeably. We further define one interconnector for each direction, so that $f = (n, m)$, $\hat{f} = (m, n)$, where f, $\hat{f} \in \mathcal{F}$. We also define subsets $\mathcal{F}^{out}_n$, $\mathcal{F}^{in}_n \subset \mathcal{F}$ that collect all interconnectors f and $\hat{f}$ that start and end at zone n, respectively. We use net transfer capacities to limit the maximum flows on interconnectors between zones in accordance with Eq. (C.12) – Eq. (C.13).

$$0 \leq F_{f,t} \leq ntc_f \qquad \forall\, t \in T, f \in \mathcal{F} \tag{C.12}$$

$$0 \leq F_{f,t} + F^{\text{adj}}_{\omega,f,t} \leq ntc_f \qquad \forall\, \omega \in \Omega, t \in T, f \in \mathcal{F} \tag{C.13}$$

Electrolyser. Eq. (C.14) and Eq. (C.15) restrict hydrogen production from power consumption $L_{e,t}$ including balancing energy $B^{\text{down}}_{\omega,e,t}$ and $B^{\text{up}}_{\omega,e,t}$ to stay between the limits of zero and maximum installed electrical capacity g^{max}_e.

$$L_{e,t} + B^{\text{down}}_{\omega,e,t} \leq l^{\text{max}}_e \qquad \forall\, \omega \in \Omega, e \in E, t \in T \tag{C.14}$$

$$L_{e,t} - B^{\text{up}}_{\omega,e,t} \geq l^{\text{max}}_e \qquad \forall\, \omega \in \Omega, e \in E, t \in T \tag{C.15}$$

Storage Equations. Storage units operate similarly to conventional electricity generation technologies in their discharge mode and similarly to electrolysers in their charge mode. To reflect all the characteristics of a storage unit with regard to balancing, Eq. (C.16) and Eq. (C.17) restrict power consumption $L_{s,t}$, including activated balancing capacity $B^{\text{down,L}}_{\omega,s,t}$ and $B^{\text{up,L}}_{\omega,s,t}$ to stay between the limits of zero and maximum installed charge capacity l^{max}_s. Further, Eq. (C.19) and Eq. (C.18) address the capacity boundaries of generation (discharge) from storage $G_{s,t}$ and the balancing adjustments $B^{\text{down,G}}_{\omega,s,t}$ and $B^{\text{up,G}}_{\omega,s,t}$ to keep within the physical boundaries at maximum $g^{\max}_s$.

$$0 \leq L_{s,t} + B^{\text{down,L}}_{\omega,s,t} \leq l^{\max}_s \qquad \forall\, \omega \in \Omega, s \in S, t \in T \tag{C.16}$$
$$0 \leq L_{s,t} - B^{\text{up,L}}_{\omega,s,t} \leq l^{\max}_s \qquad \forall\, \omega \in \Omega, s \in S, t \in T \tag{C.17}$$
$$0 \leq G_{s,t} + B^{\text{up,G}}_{\omega,s,t} \leq g^{\max}_s \qquad \forall\, \omega \in \Omega, s \in S, t \in T \tag{C.18}$$
$$0 \leq G_{s,t} - B^{\text{down,G}}_{\omega,s,t} \leq g^{\max}_s \qquad \forall\, \omega \in \Omega, s \in S, t \in T \tag{C.19}$$

Eq. (C.20) limits the stored energy $S_{\omega,s,t}$ between a lower and upper storage bound $s^{\min}_s$ and $s^{\max}_s$.

$$s^{\min}_s \leq S_{\omega,s,t} \leq s^{\max}_s, \qquad \forall\, \omega \in \Omega, s \in S, t \in T \tag{C.20}$$

The storage level $S_{\omega,s,t}$ in each time step and scenario is determined by the storage level of the previous time step $S_{\omega,s,t-1}$, adjusted by charged energy $(L_{s,t} + B^{\text{up,L}}_{\omega,s,t} - B^{\text{down,L}}_{\omega,s,t})$ and discharged energy $(G_{s,t} + B^{\text{up,G}}_{\omega,s,t} - B^{\text{down,G}}_{\omega,s,t})$. The charging and discharging efficiencies are denoted as η^{L}_s and η^{G}_s, respectively.

$$\begin{aligned} S_{\omega,s,t} &= S_{\omega,s,t-1} + \eta^{\text{L}}_s \cdot (L_{s,t} - B^{\text{up,L}}_{\omega,s,t} + B^{\text{down,L}}_{\omega,s,t}) \\ &\quad - \frac{1}{\eta^{\text{G}}_s} \cdot (G_{s,t} + B^{\text{up,G}}_{\omega,s,t} - B^{\text{down,G}}_{\omega,s,t}) \qquad \forall\, \omega \in \Omega, s \in S, t \in T \end{aligned} \tag{C.21}$$

Ramping. Conventional power plants and hydro turbines have technical limits on their ability to adjust their power output. We incorporate these limits by including ramping constraints for all dispatchable power plants $u \in \mathcal{U}$ and storage units $s \in \mathcal{S}$:

$$-r^{\text{down}}_u \leq G_{u,t} - G_{u,t-1} \leq r^{\text{up}}_u, \qquad \forall\, u \in \mathcal{U}, t > 1 \tag{C.22}$$
$$B^{\text{ramp}}_{u,t,\omega} = B^{\text{up}}_{\omega,u,t} - B^{\text{down}}_{\omega,u,t}, \qquad \forall\, \omega \in \Omega, u \in \mathcal{U}, t \in \mathcal{T} \tag{C.23}$$
$$-r^{\text{down}}_u \leq G_{u,t} - G_{u,t-1} + B^{\text{ramp}}_{u,t,\omega} - B^{\text{ramp}}_{u,t-1,\omega} \leq r^{\text{up}}_u, \qquad \forall\, \omega \in \Omega, u \in \mathcal{U}, t > 1 \tag{C.24}$$
$$-r^{\text{down},G}_s \leq G_{s,t} - G_{s,t-1} \leq r^{\text{up},G}_s, \qquad \forall\, s \in \mathcal{S}, t > 1 \tag{C.25}$$
$$B^{\text{ramp},G}_{s,t,\omega} = B^{\text{up},G}_{\omega,s,t} - B^{\text{down},G}_{\omega,s,t}, \qquad \forall\, \omega \in \Omega, s \in \mathcal{S}, t \in \mathcal{T} \tag{C.26}$$
$$-r^{\text{down},G}_s \leq G_{s,t} - G_{s,t-1} + B^{\text{ramp},G}_{s,t,\omega} - B^{\text{ramp},G}_{s,t-1,\omega} \leq r^{\text{up},G}_s, \qquad \forall\, \omega \in \Omega, s \in \mathcal{S}, t > 1 \tag{C.27}$$
$$-r^{\text{down},L}_s \leq L_{s,t} - L_{s,t-1} \leq r^{\text{up},L}_s, \qquad \forall\, s \in \mathcal{S}, t > 1 \tag{C.28}$$
$$B^{\text{ramp},L}_{s,t,\omega} = B^{\text{up},L}_{\omega,s,t} - B^{\text{down},L}_{\omega,s,t}, \qquad \forall\, \omega \in \Omega, s \in \mathcal{S}, t \in \mathcal{T} \tag{C.29}$$
$$-r^{\text{down},L}_s \leq L_{s,t} - L_{s,t-1} + B^{\text{ramp},L}_{s,t,\omega} - B^{\text{ramp},L}_{s,t-1,\omega} \leq r^{\text{up},L}_s, \qquad \forall\, \omega \in \Omega, s \in \mathcal{S}, t > 1 \tag{C.30}$$

where $r_u^{\text{down}}, r_u^{\text{up}}$ are the maximum ramping capabilities for downward and upward ramping, respectively, of conventional generator u. For storage s, $r_s^{\text{down},G}$ and $r_s^{\text{up},G}$ and $r_s^{\text{down},L}, r_s^{\text{up},L}$ are the maximum ramping capabilities for upward and downward ramping in discharge and charging mode, respectively. Furthermore, we define auxiliary variables $B_{u,t,\omega}^{\text{ramp}}$, $B_{s,t,\omega}^{\text{ramp},G}$, $B_{s,t,\omega}^{\text{ramp},L}$ to capture the generation adjustments in the balancing stage.

Balancing Costs

We assume that the costs of dispatchable units u in the balancing markets are chosen in a way that reflects the additional costs of adjusting the power output away from the day-ahead schedule. Hence we assume that for upward balancing services (generator produces more power), the cost $p_g^{B,U}$ equals $mc_u \cdot (1+\mu)$, where μ is chosen to be 20%. Similarly, the cost for downward balancing services (generator produces less power) is assumed to be $p_g^{B,D} = mc_u \cdot (1-\mu)$. By contrast, the electrolyser faces some gained or lost profits on the hydrogen market if it produces more or less hydrogen by consuming more or less power. Following a similar argument for dispatchable generators, we assume that the bid price for upward balancing services (electrolyser consumes less power) is $p_e^{B,U} = \eta_e p^{\mathrm{H}_2} - mc_e \cdot (1-\mu)$. Analogously, the cost for downward balancing services (electrolyser consumes more power) is $p_e^{B,D} = -(\eta_e p^{\mathrm{H}_2} - mc_e \cdot (1+\mu))$. Note that in contrast to dispatchable units, the electrolyser not only takes its marginal production cost into account, it further includes its opportunity cost to produce an increased or reduced amount of hydrogen.

Additional Graphs and Data

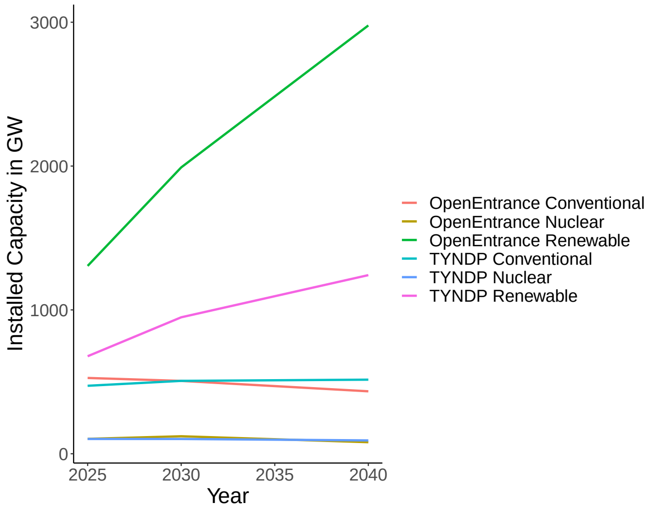


Figure C.12. Installed Capacities from TYNDP and OpenEntrance Scenarios.

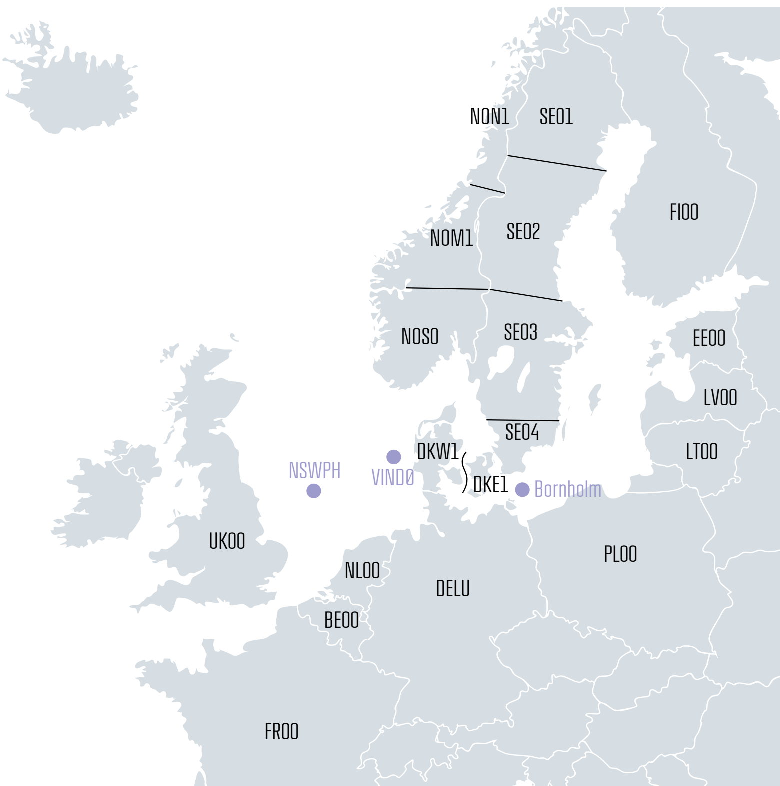


Figure C.13. Zones in the model.

Die Welt könnte wieder ein Paradies werden. Alles ist möglich.

— Erich Kästner in Pünktchen und Anton.

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