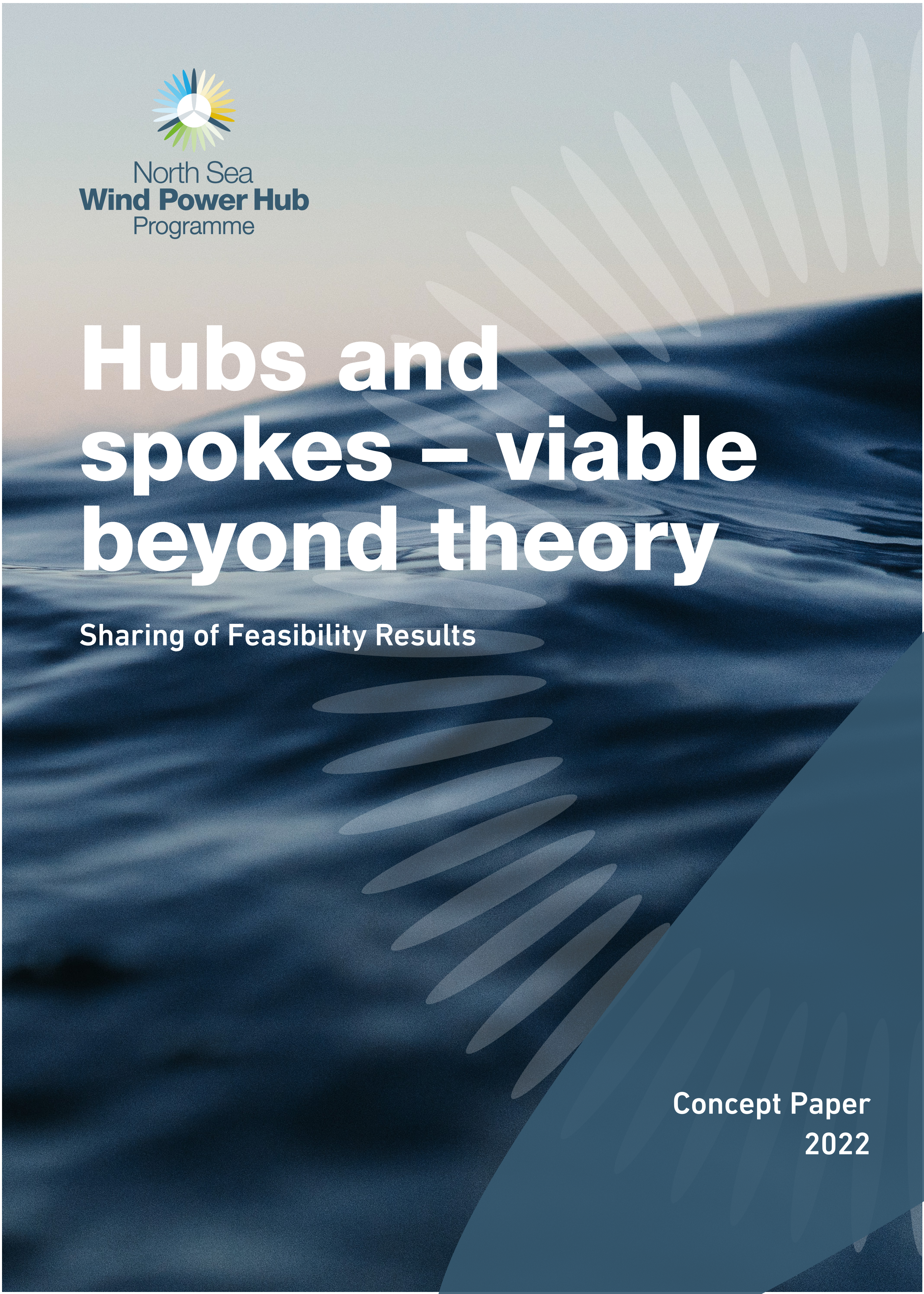

North Sea
Wind Power Hub
Programme

Hubs and spokes – viable beyond theory

Sharing of Feasibility Results

Concept Paper
2022

Co-financed by the Connecting Europe
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The NSWPH consortium

The North Sea Wind Power Hub (NSWPH) consortium provides a new approach to accelerating the energy transition and to meeting the Paris Climate Goals. Today, climate policy is largely national, decoupled and incremental. We need a new approach to effectively realise the potential of the North Sea and reach the goals of the Paris Agreement. We take a different perspective: harnessing the power of the North Sea requires a transnational and cross-sector approach to take the step-change we need.

We are committed to develop the energy infrastructure for the future, acting out of our responsibility to enable the energy transition and reaching the climate goals in time, while maximising social benefits. We leverage the expertise of the consortium companies to find solutions to the challenges and work towards our goal: realise a first hub-and spoke project in the early 2030s.

The NSWPH consortium was founded in March 2017 and consists of Energinet, Gasunie and TenneT. As leading transmission system operators of North Sea countries, we take a long term and integrated perspective on the energy transition and we are tasked to maintain security of supply.

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Content

Introduction

Our energy landscape

We can see the changes from space. Satellite photos show grey smoke from scorched earth throughout Europe, the physical consequences of a year with unprecedented temperatures. 28 European capital cities have experienced record heat in June and July. Global warming has accelerated once-in-a-century events to push boundaries every year, proving the need for our small, blue planet to transition from black and fossil energy to renewable and green.

The accelerating march of climate change is not alone in challenging us. War in Ukraine has stopped the flow of Russian oil and gas and energy prices have been driven to new all-time highs. Never throughout history have we produced more energy worldwide and still, we find ourselves in an energy crisis. In addition, the supply chains keeping the world together are strained. Vital commodities such as steel, copper and nickel needed for sustainable energy buildouts are cut off from major suppliers such as Russia and Ukraine. An increasing demand for these commodities drains the supply to the European markets. Action is needed, now more than ever, while we still can.

Collect, Connect, Convert

The North Sea Wind Power Hub achieves three vital tasks that the future green powerplant of the North Sea must be able to lift:

- Collect vast amounts of offshore wind power generated at wind farms and energy hubs in the North Sea at a few centralised locations
- Connect these hubs in a flexible network that spans the North Sea and can supply power deep into the European mainland to supply millions of consumers with green energy
- Convert surplus electricity to hydrogen to expand the uses of the green power and reduce CO_2 emissions from heavy industry, transport and more.

Steps are being taken, including strong ambitions to accelerate the energy transition in coalition agreements, bilateral and multilateral declarations, and energy summits such as the Esbjerg Offshore Wind Summit and the Baltic Sea Energy Security Summit. The goals include a staggering capacity target of 150 GW by 2050 for the North Sea and 20 GW of electrolyser capacity by 2030. Major players in European energy are working hard to find the best way forward. And we are proud to be among them with our European Project of Common Interest.

We need to make the right choices now. In this paper, the North Sea Wind Power Hub (NSWPH) consortium presents the vision for a North Sea renewable energy build-out that maximises efficiency of energy production and secures a concept which allows to capitalise on every technological advance we make. All for the North Sea to become the new green powerplant of Europe.

Our vision

The European Commission and national governments have voiced clear ambitions for the North Sea. During the Esbjerg offshore wind summit in May of 2022, Denmark, the Netherlands, Germany, and Belgium agreed to jointly develop the North Sea as a green power plant for Europe[I]. Offshore wind capacity targets were confirmed at 65 GW by 2030 and 150 GW by 2050, signifying the acceleration of renewable electricity and hydrogen developments. Similarly, a joint electrolysis capacity target is set at 20 GW for 2030. The agreement states that the power plant will consist of multiple connected offshore energy projects and hubs for electricity and hydrogen transport. The importance of cross-border cooperation and interconnection is stressed in the multilateral and bilateral agreements.

In our first Pathway study (highlighted in this report) we demonstrate the need for multiple electricity corridors in the North Sea to connect offshore wind locations. In the feasibility phase of the NSWPH project, we introduced the distributed hub concept, which includes three offshore energy hubs in Denmark, the Netherlands, and Germany. This is a bold step to building the interconnected North Sea electricity and hydrogen infrastructure.

The hub-and-spoke-model allows for an internationally coordinated and modular buildout that achieves three vital tasks that the future green power plant in the North Sea must be able to perform: *collect, connect*, and *convert*. The NSWPH project has moved from an ambitious novel concept to receiving concrete political buy-in. In that sense, the landscape has changed completely over the last few years as there are concrete national projects underway following the concept. In the pre-feasibility phase[II] and the feasibility phase, we have collaborated with various stakeholders including Danish and Dutch ministries under their Memorandum of Understanding. We are proud to have contributed to the changing landscape of North Sea offshore wind development through continuous knowledge development and sharing.

In the feasibility phase, we found answers to how we can develop the NSWPH project. This includes detailed technical analyses of hub foundations, electrical and hydrogen infrastructure, and power-to-gas, as well as energy system studies and policy and market assessments. In addition, we further develop the cost-benefit analysis framework for hub-and-spoke concepts and successfully apply this to possible/likely configurations.

Project of Common Interest

The North Sea Wind Power Hub project was granted the Project of Common Interest (PCI) status in 2019[III]. Projects of common interest are key cross border infrastructure projects that link the energy systems of EU countries. The PCI status has allowed the NSWPH consortium to apply for, and subsequently receive, Connecting Europe Facility funding.
This European funding programme supports the development of high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy, and digital services. With this publication, we demonstrate the feasibility of the NSWPH PCI project and reach Milestone 30 of the NSWPH CEF grant agreement.

Why this concept paper?

In this concept paper we present the key results from the feasibility phase of the NSWPH project. During the feasibility phase, we further deepened our understanding of the technical, economical, and regulatory aspects of the hub-and-spoke concept. In previous phases we identified the characteristics of a hub-and-spoke project and what is needed to realise such a project. In the feasibility phase, we aim to answer how we can realise such a project.

The findings include feasible technical concepts and layouts, drivers for costs and benefits of the concept, and methods for market and regulatory framework implementation. Previous concept papers are accessible at the following webpage www.northseawindpowerhub.eu/vision.

Reading guide

This report is structured around the key findings within our core activities. It starts with ‘System Integration’, which deals with reducing the temporal and spatial mismatch of supply and demand. We show that the hub-and-spoke concept is a feasible and efficient solution for large-scale integration of offshore wind in the North Sea. The chapter on ‘Technical feasibility’ describes the major progress we have booked on the technical feasibility of electrical and hydrogen system components. We demonstrate the technical feasibility of these different building blocks of the hub-and-spoke concept. In ‘Cost and Benefits’, the novel approach to cost benefit analysis (CBA) calculations is presented. We also show that the hub-and-spoke concept is future proof and even cost competitive to alternative configurations in the short term. Finally, the chapter on ‘Regulatory and Market Design’ shows how we can implement the hub-and-spoke concept from a regulatory perspective.

Main Insights

In the feasibility phase of the NSPWH project, we try to answer the question how hub-and-spoke projects can be developed. We continuously conduct analyses to support decision-making of national governments and investigate the broader energy system impact of the concept, the costs and benefits, the regulatory changes required and a fitting market setup. In this paper, we share our insights on four core activities that we developed during the feasibility phase of the first hub-and-spoke project:

System Integration

What are the challenges and drivers to integrate large scale offshore wind in an energy system in transition and which design principles can be determined for the energy-infrastructure at the North Sea?

Our Main Insight
Multiple electricity corridors in the North Sea can be identified to connect offshore wind locations and transport the energy via hubs to shore. The corridors develop consistently between 2030 and 2050 and follow a North-South direction or East-West direction with potential branches to surrounding countries. For the electricity and hydrogen system the use of electrolysers is essential to realise system integration.

Cost & Benefits

How do we calculate the costs and benefits of hub-and-spoke projects given their unique characteristics to collect, connect, and convert energy?

Our Main Insight
We successfully tested CBA methodologies that we developed for the hub-and-spoke concept and created a stepwise methodology for cost-benefit analyses.

Technical Feasibility

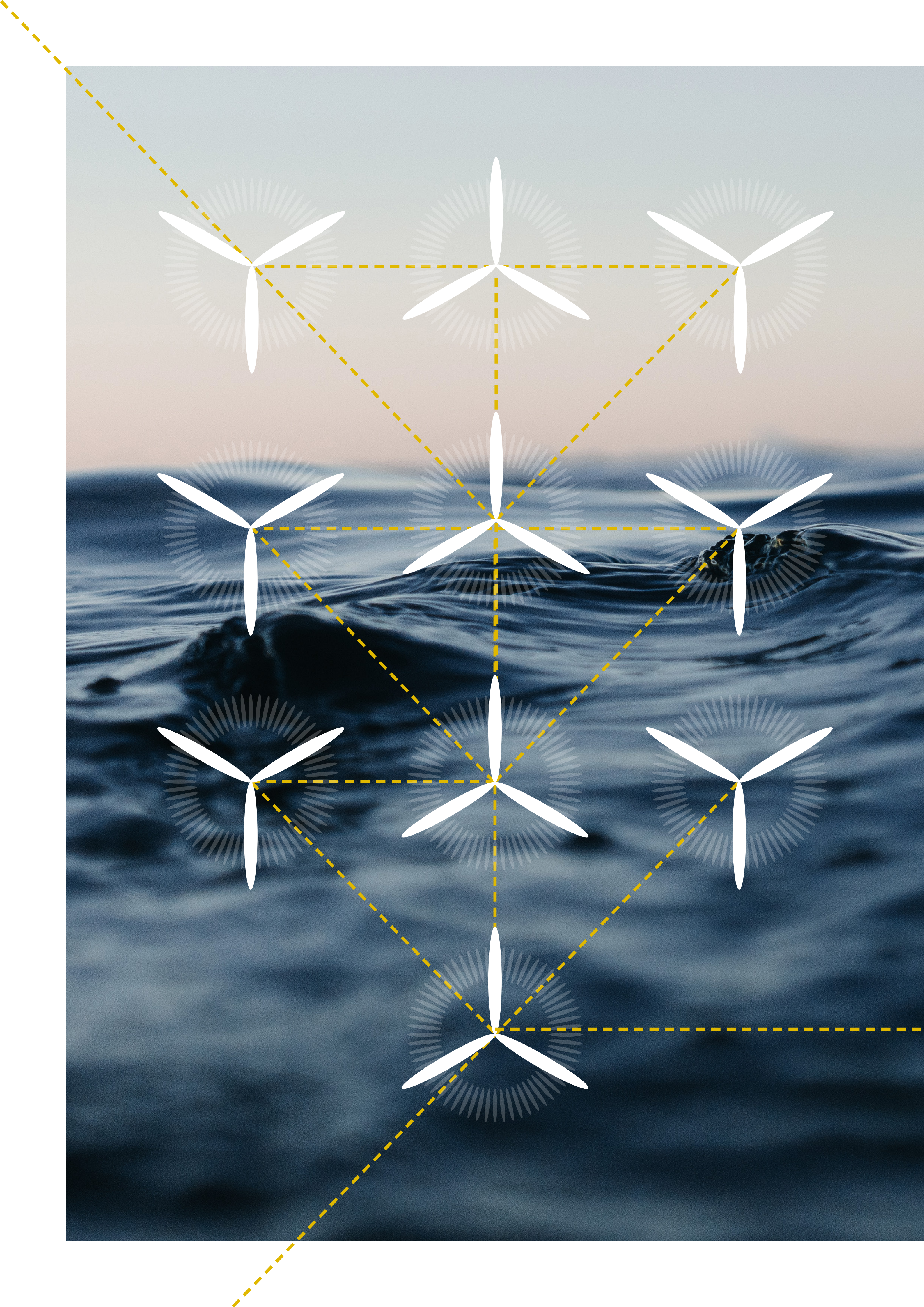
What are the technical design principles for individual system elements of a hub-and-spoke project?

Our Main Insight
All elements of a hub and spoke project, including substructure, high voltage direct current (HVDC) infrastructure, offshore electrolysis, and hydrogen infrastructure are technically feasible. Modular design of offshore energy hubs is possible to create future flexibility and extendibility. Required functionalities can be realised on platforms or artificial islands.

Regulation & Market Design

What choices are needed by national and European governments to provide sufficient investment clarity for hub-and-spoke project and offshore wind roll-out?

Our Main Insight
Offshore bidding zones are more robust in providing socio-economic benefits compared to the home market setup. We show that the implementation of offshore bidding zones can be realised in 9 – 18 months under current regulation.



System Integration

What have we learned

- ✓ Multiple electricity corridors in the North Sea can be identified to connect offshore wind locations and transport the energy via hubs to shore. The corridors develop consistently between 2030 and 2050 and follow a North-South direction or East-West direction with potential branches to surrounding countries.
- ✓ For the electricity and hydrogen system the use of electrolysers is essential to realise system integration.
- ✓ The hourly data from the first Pathway study show the interaction of the electricity and hydrogen system under different circumstances for pathways to 2050. We demonstrate the importance of additional transmission, storage, and conversion investments to integrate large scale offshore wind in the future energy system.
- ✓ Offshore electrolysis is technically feasible, and the grid integrated offshore power to gas study shows placing electrolysis close to the renewable energy source (offshore wind farm) can result in infrastructural benefits.
- ✓ We identified four guiding principles for a hydrogen-enabled integration of large-scale intermittent renewable energy.

What will we do next

- To learn further about effective integration of large-scale offshore wind we will continue to conduct explorative pathway studies. Both for electricity and hydrogen, ongoing developments, learnings and insights are updated in the model and are part of a second Pathway study where we will explore multiple sensitivities and assess how these changes effect offshore wind roll-out.

Breakthrough

Energy system modelling consistently shows the importance of an internationally coordinated meshed offshore grid with North-South and East-West connections for offshore wind and energy markets. Offshore wind energy from the North Sea integrally serves the electricity and hydrogen system.

A hub-and-spoke concept is developed to benefit the system integration of large amounts of offshore wind energy, increase security of supply, and support decarbonisation of all sectors. Deployment of large amounts of offshore wind in the northwest European energy system requires careful integration, as there can be a large mismatch between supply and demand in both time and space. Through energy system studies and techno-economic analyses, we have assessed which energy-infrastructure (transport, conversion, and storage) is required to integrate large-scale offshore wind, considering the impact on the energy-infrastructure both offshore and onshore.

The aim of the first Pathway study was to learn how the integration of large-scale offshore wind is done effectively and in ways that maximises long-term socio-economic welfare while ensuring security of supply. The objectives of the study were to:

- deepen the understanding of the offshore wind integration challenges on both a national and transnational level,
- understand the drivers of effectively integrating large scale offshore wind into the energy system, considering the country or regional specific energy system context, and
- determine the design principles for possible integration routes, in the context of the roll-out pathway of the first and following hub-and-spoke projects, thereby supporting decision making for the first hub and spoke project to be realised in the early 2030s.

In other energy system studies[IV], we have assessed the energy system and infrastructure choices that benefit the cost effective and efficient integration of offshore wind in the northwest European energy system.

Our first Pathway study presents potential end-pictures and pathways through energy infrastructure optimization modelling, with the focus on minimizing cost of energy-infrastructure on the long term (2050). We employed a partial equilibrium model to find the least-cost economical dispatch and capacity expansion solution for the represented energy system. Energy system scenarios (electricity and hydrogen demand, and power supply capacity) were fixed whereas infrastructure (onshore and offshore), conversion, and storage capacity as well as dispatch of power sources were optimised by the model.

Key message 1

Multiple electricity corridors in the North Sea can be identified to connect offshore wind locations and transport the energy via hubs to shore. The corridors develop consistently between 2030 and 2050 and follow a North-South direction or East-West direction with potential branches to surrounding countries.

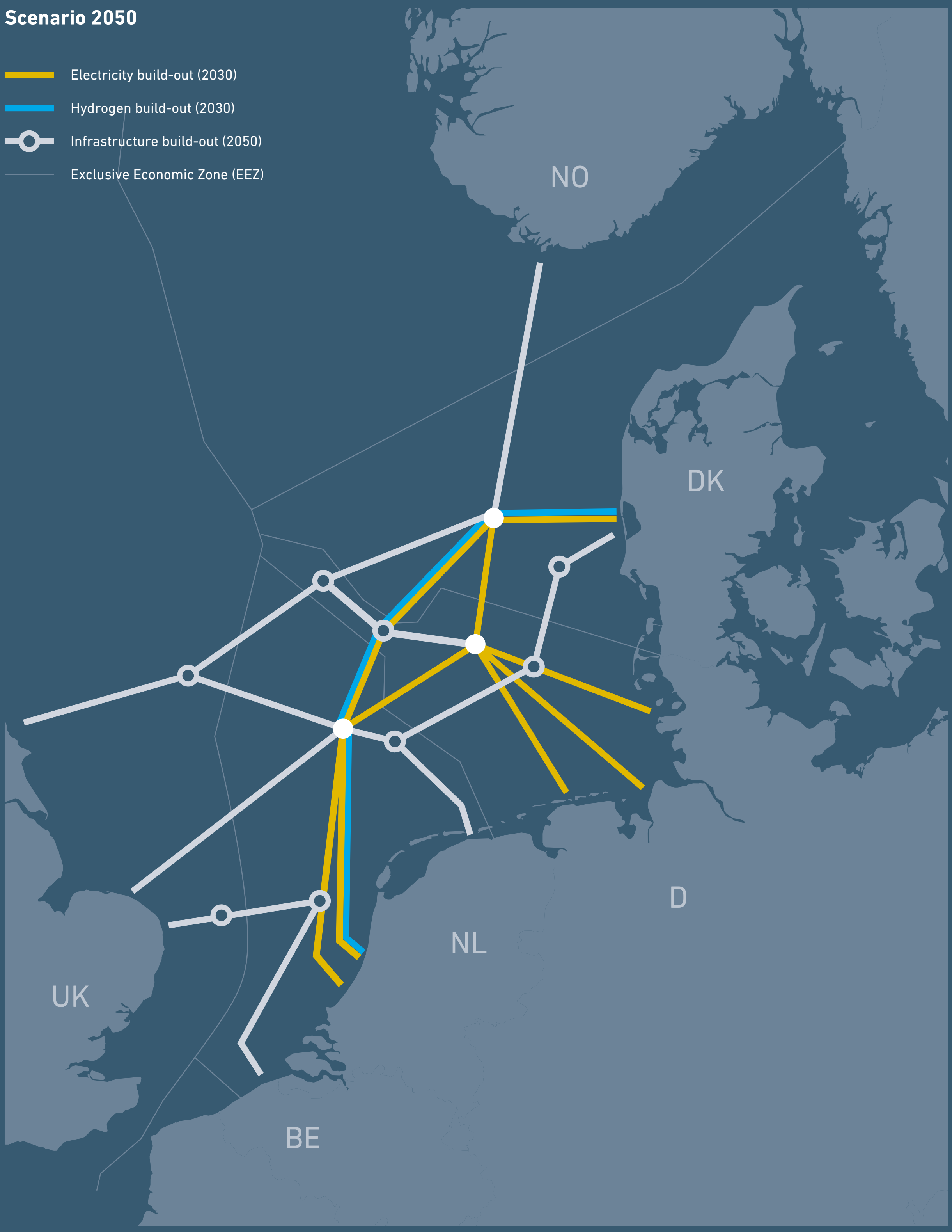
We compared multiple energy system scenarios and strategies for the roll-out of offshore wind. The four energy system scenarios are characterised as a combination of either high gas demand or high electrification and modest or increased renewables deployment. The two studied roll-out strategies for offshore wind are:

1. *Internationally coordinated:* offshore wind farms can connect radially to the respective home country, to other wind farms and to neighbouring countries
2. *National incremental:* offshore wind farms can only connect radially to the respective home country

The additional buildout via offshore hubs exhibits a lower number of connections to shore and direct connections between two countries. Still, total transmission investments are large, and in the most ambitious scenarios, the transmission system capacity is doubled between 2030 and 2050. Relatively, the offshore connections in the North Sea represent only a small share of the total transmission needs.

An important feature of the Pathway modelling is the capacity expansion of the onshore and offshore

Figure 3.1 | The results consistently show north-south and east-west electricity corridors in the North Sea to connect offshore wind farms and countries for 2050.



power grids. The results consistently show north-south and east-west electricity corridors in the North Sea to connect offshore wind farms and markets in 2050. These corridors are robust throughout the four energy system scenarios. These results tell us that the concept of hub-and-spoke projects is valid, and that a meshed offshore grid connecting both offshore wind and providing interconnection is an efficient method for integrating large amounts of offshore wind in the northwest European energy system.

Key message 2

We demonstrate that electrolysers are crucial to realise system integration of offshore wind for the electricity and hydrogen system.

Concepts | Power-to-gas and gas-to-power

Power-to-gas means the conversion of electrical power into a gaseous energy carrier such as hydrogen. Further processing may be applied to generate e.g., methane. Within the context of NSWPH, power-to-gas is synonymous with power-to-hydrogen through electrolysis. Gas-to-power is the reverse process of converting chemical energy from a gaseous energy carrier to electricity, either in a fuel cell or gas-fired power plant.

Future energy scenarios show a significant increase in hydrogen demand across multiple sectors, including industry and transportation. European and national directives for renewable fuels of non-biological origin will further help establish a hydrogen market. These industries include cement, steel, and chemicals production. Our energy system modelling studies show that hydrogen production with electrolysis is essential to the integration of large-scale deployment of renewable energy.

Offshore wind sourced power-to-gas can be supplemented by hydrogen imports to provide a constant stream of molecules for hard to abate sectors. At the same time power-to-gas and gas to power can balance the electricity network in times of high or low renewable energy production.

In our first Pathways study, we demonstrate the important role that electrolysers play in an integrated electricity and hydrogen system. Electrolysers are essential to uptake large amounts of offshore wind electricity without significant/excessive onshore electricity infrastructure build-out while delivering valuable green hydrogen to demand centres.
Our Pathways model optimised the locations of electrolysers in the system: electrolysers are consistently placed in areas where there is a large amount of renewable electricity production. It is therefore a critical element in sector coupling of electricity and hydrogen systems.

We demonstrate that domestic hydrogen production within an integrated energy system is cost-competitive with hydrogen imports from other regions. In an integrated energy system, renewable electricity and hydrogen production are optimised to deliver the highest system value. The results of our analyses show that grid-integrated electrolysis results in a higher utilisation grade of key assets, including the electricity and hydrogen transmission grid, and electrolysers. In addition, curtailment of renewable electricity sources is reduced.

Key message 3

The hourly data from the first Pathway study show the interaction of the electricity and hydrogen system under different circumstances for pathways to 2050. We demonstrate the importance of additional transmission, storage, and conversion investments to integrate large scale offshore wind in the future energy system.

System integration deals with the reduction of mismatches between supply and demand, both in time and space. Our existing energy system is based on fossil fuels that can be stored in large amounts against relative low cost. In a normal market this ensures a continuous supply of energy. Transitioning to a system where variable renewable generation makes up a significant portion of our energy supply requires investments in system flexibility. We demonstrate the importance of investments in new transmission assets, conversion, and storage.

We identify three types of flexibility to allow for increased electricity and hydrogen system integration of offshore wind energy: *large-scale flexible electricity consumption, flexibility from demand response*, and *time shift flexibility*. We observed that a combination of large amounts of renewable energy production, high interconnectivity between countries and smart use of flexible technologies like batteries and power-to-gas can serve the European electricity system for the vast majority of hours in the year.

Large-scale flexible electricity consumption which is placed on the border of the existing electricity grid to prevent congestions in the grid and to allow an economically viable additional buildout of intermittent renewables. This type of flexibility allows for coupling of the electricity and hydrogen systems and can help solve the temporal mismatch of demand and supply. New additional transmission lines could also enable the utilisation of the "excess" electricity at large demand centres. The issue is that the utilisation rate of additional transmission lines would be low, which would significantly increase the cost per MWh of this option, compared to flexible electricity consumption before the electricity enters the main grid. The Pathways study demonstrated that coupling the electricity and hydrogen system via electrolysis allows for more direct electrification, higher utilisation of transmission assets, and more offshore wind to be installed within the same grid capacity.

Flexibility from demand response within the current grid aims at reducing the immediate electricity demand at times of low offshore wind production. This type of flexibility will decrease the demand for dispatchable power which is often more expensive and less efficient than intermittent renewables. It can be provided by heat pumps, electric boilers, battery electric vehicles, industrial processes, electrolysers, and other technologies. As a result, the demand is reduced when renewable generation is not sufficient. The Pathways study demonstrated the role that this type of flexibility can play to solve short-term mismatches in supply and demand. Variable production of renewable electricity sources can be stored in batteries, for example, at times when renewable production exceeds immediate demand. The stored energy can be delivered to meet the demand when renewable energy production is lower.

Time shift flexibility relies on longer term conversion and storage solutions. This is the ability to store electricity in periods with a surplus/usually low prices and deliver it back in periods with deficits/usually high prices. It can be provided by a power-to-gas and gas-to-power route, which we have shown to be both feasible and cost-effective[V], and complement other options like imports from hydropower in external regions. Back-up capacity like hydrogen gas-to-power is only used for a limited amount of time but can be critical in delivering power at times of low renewable energy generation. The Pathways study demonstrated how hydrogen storage and gas-to-power can complement hydro-power flexibility from other regions at times of low domestic renewable energy production.

Key message 4

Offshore electrolysis is technically feasible, and we show that placing electrolysis close to the renewable energy source (offshore wind farm) can result in infrastructural benefits.

We have established the important role of electrolysis to provide an integration function for the electricity and hydrogen system. The first Pathway study shows mainly onshore investments in electrolysis as well as large investments in electrical and hydrogen infrastructure and storage solutions. Offshore electrolysis was not a viable option in the current Pathway model set-up due to the input parameters used in the model.

In our energy system study on grid-integrated power to gas, we demonstrated how electrolysis can provide energy system benefits. Placing electrolysers close to the renewable energy source can alleviate the electricity grid build-out need and provide valuable green hydrogen to demand centres. When considering large scale offshore wind development in the North Sea, a first step is to locate power-to-gas near landing zones of offshore wind. Here the power can either be converted to hydrogen transmitted as electricity to the electricity grid. A secondary step could be to locate power-to-gas at an offshore location, such as an energy hub. The primary advantage is that electrical peak-transmission capacity from offshore to onshore can be reduced. This option, however, is only considered realistic for wind parks which are far out at sea and require High Voltage Direct Current (HVDC) connections due to their distance.

Key message 5

We identified four guiding principles for hydrogen-enabled integration of large-scale intermittent renewable energy.

We demonstrated the added value of electrolysers for an integrated, reliable energy system with other flexible electricity consumers. However, to reach an efficient cross-border, cross-sector energy system with maximal usage of renewable energy and net socio-economic benefits for consumers, market designs and regulatory frameworks should provide balanced and appropriate incentives for investment.

We have developed four guiding principles for an efficient cross-border and cross-sector energy system[VI]:

1. A *timely development of a hydrogen market* and infrastructure, both within and between regional, industrial clusters. Hydrogen infrastructure is needed to develop a mature European market for green hydrogen. On the other hand, without any green hydrogen production and enough green hydrogen demand, there is no need for hydrogen infrastructure. Hence, we need coordinated development of an EU wide hydrogen market and infrastructure (both regional infrastructure in industrial clusters and connections between these clusters), including clear roles and responsibilities to make the market function efficiently.

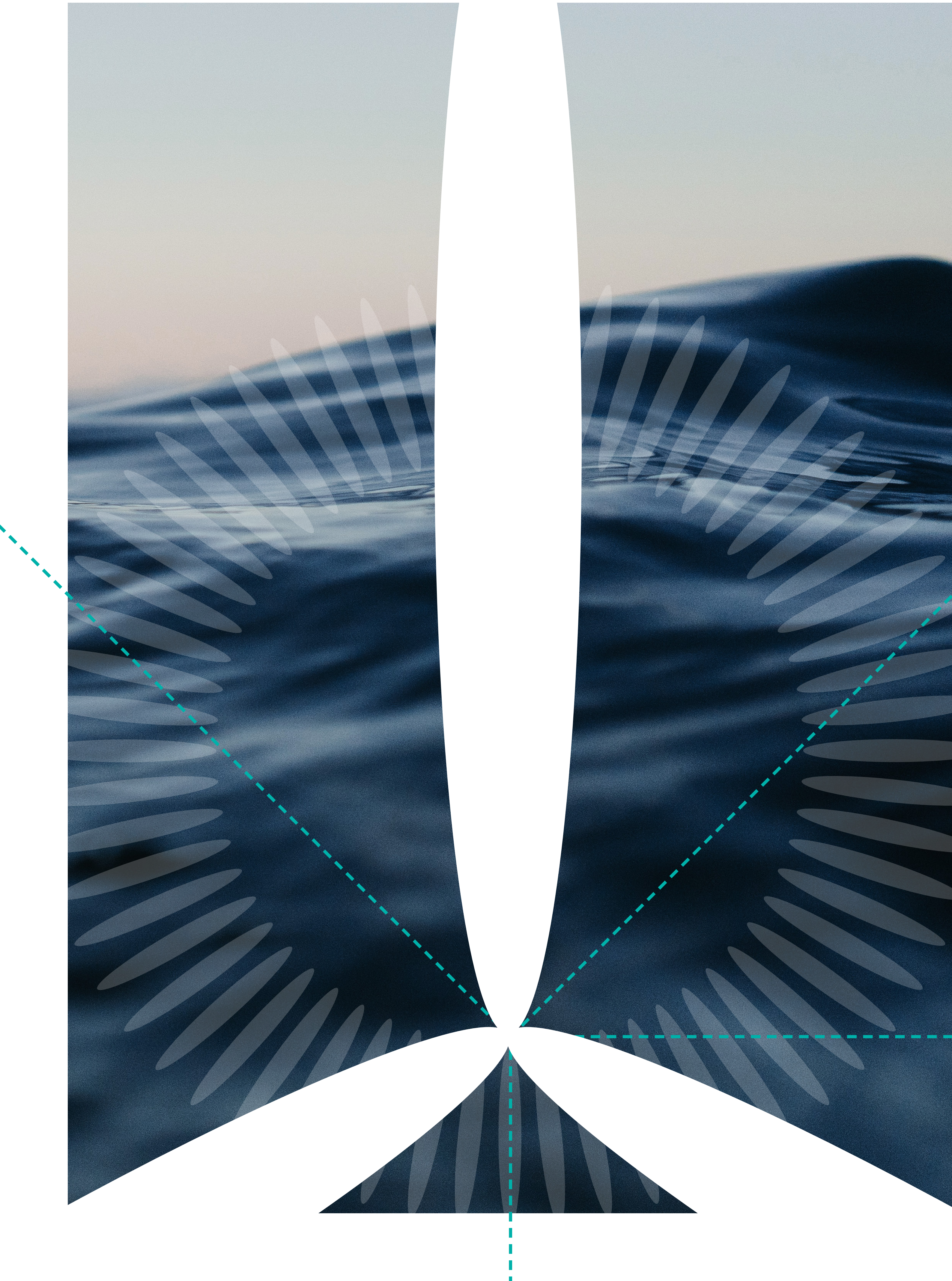
2. Mechanisms which *provide incentives for efficient* locations for electrolysis from an energy infrastructure perspective. Energy system modelling shows that it is most efficient from a transmission system perspective to place electrolysers close to renewable electricity generation. This can reduce the need for onshore electricity network build out while existing gas infrastructure in the proximity to landing points could be beneficial to reuse for hydrogen transport. Combining planning of electricity grids, gas grids, and electrolysis on a national and European level can support efficient development of our future energy system.

3. Mechanisms which support *timely construction and upscaling of electrolysers* by e.g., providing investment certainty allowing to kickstart large scale flexible consumption. Despite the relatively high technological readiness level of small-scale electrolysis, significant steps need to be taken to reach GW scale electrolysis. The main challenges in the technological development of GW scale electrolysis are the costs of producing hydrogen at a large scale and the competition and production costs of these green molecules compared with the fossil-based alternatives including CO_2 taxation. To reach GW scale electrolysers in 2030, upscaling towards projects of 100-500 MW in the coming period will be essential to drive costs down and realise production benefits for the electrolyser systems.

4. Market and regulatory mechanisms which provide *dispatch incentives to improve optimal usage of renewable energy and infrastructure*. The operation of an electrolyser will mainly depend on the price spread between electricity and hydrogen. It is important to ensure that the electrolyser only operates on electricity from renewable sources. Dispatch incentives could include higher CO_2-pricing or location and time-specific guarantees of origin.

Next Steps | Continuous improvement of the current model and underlying data and update to the Pathways study.

The goal is to assess how we can integrate large scale offshore wind in the electricity and hydrogen system. We continue to improve our modelling toolbox to determine where offshore wind should be connected via offshore energy hubs. Ongoing developments, learnings and insights are updated in the model and will serve as the basis for new Pathway modelling studies.



Technical Feasibility

What have we learned

- All elements of a hub and spoke project are technically feasible. This includes caisson islands as a feasible alternative for hub foundation, direct-current (DC) interconnection, 110 and 132 kV offshore wind farm inter-array cables, AC and DC hub topologies, offshore and onshore hydrogen production, and repurposing of existing gas pipelines for hydrogen transport.
- Modular design of offshore energy hubs is preferred to create future flexibility and extendibility. This requires a minimum number of design choices and 5 – 10% of anticipatory investments.
- Significant supply chain risks must be addressed for electrolysers, HVDC components and hub foundations.

What will we do next

- We will continue to deepen our technical understanding of hub-and-spoke elements to further develop the concept over the next year.
- We will take the first step towards development of a suitable grid code for multi-vendor HVDC systems in the study Functional requirements for Multiterminal systems.
- We will continue to deepen our understanding of technical and economical understanding of integrated systems and interconnections.
- The NSWPH consortium will further develop and assess semi-optimised power-to-gas concept designs for caisson islands as well as grid-integrated hydrogen offshore wind turbines throughout 2022.
- Developing operational philosophies that consider the effect of hydrogen production profiles, pressure levels, pressure fluctuations and temperature on the compatibility of the pipeline material with hydrogen.

Our recommendations

- To maintain the expandability and interoperability, it is necessary for TSOs to develop a common protocol to be satisfied by each manufacturer.
- There is a need to have a sound regulatory basis which would incentivise, remunerate, and regulate anticipatory investments with the goal of creating interfaces for modular growth.
- Clear ownership, governance and conflict resolution rules for electricity and hydrogen must be in place from the beginning of hub development.

Breakthrough

We show that both onshore as well as offshore electrolysis are technically feasible at multiple GW scale. From a total integrated system perspective, the CAPEX of the offshore power-to-gas design is comparable to onshore solutions.

The technical feasibility assessment of the NSWPH programme focused on different technical and operational aspects of a particular configuration of the hub-and-spoke concept; a distributed hub concept with three interconnected hubs in the Netherlands, Germany, and Denmark. This chapter presents the main findings of several technical feasibility analyses on individual elements of a hub-and-spoke concept as well as overarching principles such as modular design and supply chain risks.

The optimal solution for the technical concept design of a hub-and-spoke project is the one which minimises the cost of the electrical systems and maximises the electricity market profit, while satisfying a set of minimum system security constraints. The case studies that have been developed within the NSWPH project in alignment with the Dutch and Danish ministries under their Memorandum of Understanding are translated to technical concept designs. This includes a high-level electrical design and considers, among others, onshore grid connection points, substation and circuit breaker configuration, and fault protection strategy.

Key message 1

All elements of a hub and spoke project, including substructure, HVDC infrastructure, offshore electrolysis, and hydrogen infrastructure are technically feasible.

We focused on different technical and operational aspects of a specific configuration of the hub-and-spoke concept. The configuration consists of a distributed hub concept with three interconnected hubs in the Netherlands, Germany, and Denmark. In our work, we demonstrated the feasibility of different aspects of the project, including offshore hub foundations, HVDC infrastructure, large scale power-to-gas, and hydrogen infrastructure. In addition, we identified focus areas and recommendations for future work.

The key results of the feasibility phase will be used in the ongoing support and interactions with policy makers and other relevant stakeholders. We will build further on the studies and further develop the hub-and-spoke concept over the next year.

Key message 2

An offshore island constructed with caissons is a feasible technical alternative for energy hubs in the North Sea.

One of the key building blocks and decisions to be taken in the development of a hub-and-spoke project is the design and engineering of substructures and hub foundations. The consortium has previously analysed the design criteria and constructability of different foundation types and substructures for a hub including platform setups with different types of substructures, a sand island concept, and a caisson island concept. In the feasibility phase, we studied the caisson island in more depth to achieve a knowledge level equal to that of the other types of substructures.

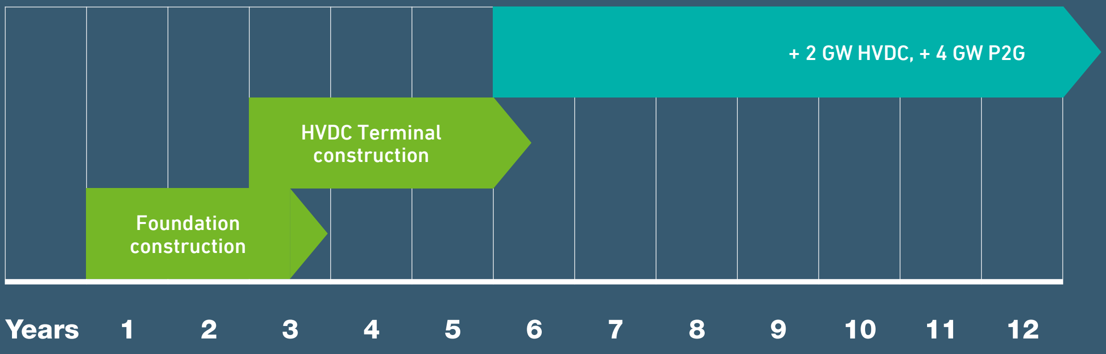
Possible technical concepts of a caisson island are analysed with consideration of prefabrication sites, transport options, as well as the stability of the structure in harsh conditions of the North Sea. A phased timeline is applied for the development of the caisson island, initially hosting 4 GW HVDC capacity, and in a second phase, 6 GW HVDC and 4 GW power-to-gas capacity. We conclude that an offshore caisson-based island is feasible for the North Sea. The maximum depth for a caisson island in the North Sea is 50 meters. However, building permanent islands in water depts more than 35 to 40 meters in challenging sea conditions of the central/ northern part of the North Sea is seen as a sizable risk, even after 2030.

The estimated construction time for the first phase (4 GW HVDC) of the island is approximately 5 years. The total area for a 4GW layout including revetments and caisson varies for the different location analysed by the NSWPH from 350m x 350m to 350m x 460m. Additional area for a second phase with 2 GW of HVDC and 4GW P2G requires significant area of up to 80 ha.

Key message 3

For long-distance interconnection, direct current (DC) technology is found to be a better solution with lower total cost than alternating current (AC) technology.

Figure 4.1 | The construction of the island substructure takes some 30 months; an additional 36 months is estimated for the HVDC terminal. Terminal construction can be started after 24 months. The second phase of the island (adding 2 GW of HVDC and 4 GW of P2G capacity) is expected to take 5 – 7 years (excluding permitting procedures). However, uncertainty remains whether phase two of the island should consist of caissons, an expansion of the original island using rubble mound revetment or satellite platforms.



For larger distances and high internal interconnection capacities between the hubs, the direct current (DC) technology seems to be the best design choice. For small distances and low internal interconnection capacities, the alternating current (AC) or hybrid AC/DC options may be envisaged. The DC concept does come with a substantially higher CAPEX compared the AC concept. However, AC cannot play the same role of interconnection power transfer as DC due to its strict limitation of the interconnection power capacity and transmission length.

Protection of the DC grid is seen as one of the major challenges. The appropriate detection and clearance of a fault in a DC system is essential to ensuring a safe and reliable grid. It is critical that a multi-terminal DC grid (such as the hub-and-spoke project) does not jeopardise the onshore AC system grid criteria in maximum loss of load or generation. We assessed three Fault Clearing Strategies (FCS) for DC multi-terminal grids. We showed that only the full selective strategy can fulfil the current AC system requirements and is the preferred solution for multiterminal DC grids. The full selective strategy is defined by PROMOTioN[VII]: "the strategies in this category aim at minimizing the impact of DC faults to the AC grid by ensuring continuous operation of the entire DC grid in case of DC faults. To do so, every line (and ideally every bus) must be individually protected."

Without Direct Current Circuit-Breakers (DCCB), any fault in a connected DC system will result in the whole system going offline. As a result of losing multiple DC stations, it may result in parts of the connected AC system going offline as well. With DC circuit breakers, a fault in the DC system can be isolated, and as a result, the rest of the connected DC system can continue operation. Considering the current capabilities of different protection technologies, Hybrid DCBBs are recommended to limit the size of DC reactors and therefore the risks of instability on the DC grid.

Concepts | Fault Clearing Strategy is the action to eliminate a fault and ensure a fast recovery of the system.

Key message 4

Inter-array voltage levels of 110 kV and 132 kV are the most economical solution for offshore wind farm design.

In addition to the grid topology and protection strategies, we assess the feasibility of raising the offshore windfarm inter-array voltage levels to 110 kV, 132 kV and 150 kV. Under the same wind farm layout, a higher voltage level inter-array system will require smaller-sized cables to accommodate the same amount of power flow transferred through each string. This also means, higher voltage level systems can have more wind turbine generators attached to a single string if required, providing greater flexibility when altering the layout of the wind farm. This potentially could be of great value to the developers as the total inter-array cable lengths can be shorter with fewer strings needed.

A cost-benefit analysis (CBA) across the four voltage levels and three different wind farm layouts demonstrate which configuration is the most economical solution for the wind farm developers in terms of both capital expenditure (CAPEX) operational expenditure (OPEX), electrical losses, and failures. We conclude that a 110 kV system with a 6 by 6 OWF layout is the most economical solution and that the 132 kV configuration is only slightly less favourable.

Key message 5

Both AC-coupled as well as DC-coupled hub topologies are feasible to stabilise the offshore HVDC network.

We take two main hub topology solutions under consideration: a multiterminal DC-coupled hub where multiple HVDC links are interconnected on the DC side of the offshore converters, and a multi-terminal AC-coupled hub where the HVDC links are interconnected on the AC side of the offshore converters. We have reviewed and tested methods for controlling active power flows in normal operation for the two different main hub topologies[VIII]. In addition, we have assessed the offshore *hub stability* for an AC-coupled and a DC-coupled hub topology.

Concepts | Hub topology refers to the network of interconnections between circuit components, including offshore wind farm feed-in and interconnectors.

The key findings on control strategies are:

- *DC-coupled hub:* Active power can be controlled properly even for extreme contingencies such as the outage of the entire wind farm connected to a converter (around 1 GW). One major limitation observed in this configuration was that a power mismatch in a HVDC pole (positive or negative) can only be solved in a converter of similar sign (positive or negative). This limits the ability of a DC-coupled hub to deal with power mismatches in one of the poles.

- *AC-coupled hub:* The main challenge for this configuration is to operate all offshore converters in parallel. Instead of individual controls for each DC connection to the AC side of the hub, a master controller would be required for the coordination of the active power among the converters.

We conclude that active power control of the hub can be achieved by having a properly designed control strategy. Some advantages were observed for the AC hub configuration, mainly due to the higher level of flexibility of control concepts.

Both DC and AC hub topologies can *stabilise* the offshore hub. It is demonstrated that the hub topologies can maintain offshore stability for the set of large and small disturbances considered. One advantage of the AC coupled hub over the DC coupled hub is that it is possible to keep the wind farms connected and ride through internal offshore converter faults, whereas in the case of the DC coupled hub, wind farms must be tripped as the sole connection point to the HVDC system is lost. However, the control for the AC-coupled hub is more complex compared to the DC-coupled hub. Therefore, it is concluded that both topologies represent feasible topologies to stabilise the offshore network and that the preferred topology should be selected based on other technical inputs and an economical evaluation.

Call to action | To maintain the expandability and interoperability, it is necessary for TSOs to develop a common protocol to be satisfied by each manufacturer.

Having multiple HVDC component manufacturers means having to ensure compatible control strategies and system requirements. A multi-terminal DC grid will consist of multiple elements developed separately and will therefore likely be supplied by different manufacturers. Interoperability of these elements can be governed by a system protocol that includes high-level control structure and the signals to be communicated between devices and the master controllers. It is up to the TSOs to develop such a protocol that stipulates the common functionality of individual system elements.

Key message 6

The lack of an offshore grid code makes it challenging to correctly stipulate control functions to achieve satisfactory HVDC offshore system performance, though it is not a showstopper.

An important aspect of the feasibility analysis of the NSWPH project is to identify and address the potential risks related to the control and protection of the system. The hub consists of multiple HVDC systems, many wind farms and possibly hydrogen generation facilities. The HVDC links are implemented with a bi-polar configuration and submarine cables at very high DC voltage. Both DC connected and AC connected hub concepts require sophisticated control and protection methods. Incorrect operation of one element of the hub can affect other elements further down the system. Grid codes exist to ensure correct operation of transmission systems and achieve satisfactory system performance. Alternatively, TSOs can make bilateral agreements in infrastructure projects that could function as a grid code.

Multi-vendor and multi-technology offshore wind farm and HVDC systems could be located at the same offshore hub or interconnected at several offshore hubs. Currently, the extent of grid code compliance is limited to the interface point between the offshore infrastructure and onshore grid. In case of meshed offshore infrastructure, each offshore transmission asset should comply with the same grid code to ensure stable grid operation.

While the grid codes have previously been extended with requirements for offshore wind farm and HVDC connections, they still lack sufficient details to govern industrial applications with similar levels of complexity as hub-and-spoke projects. The lack of sufficient offshore grid code makes it difficult to stipulate control functions for satisfactory offshore system performance. This can potentially lead to interaction issues between various systems.

Next Step | NSWPH will take the first step towards development of a suitable grid code for multi-vendor HVDC Systems in the study Functional Requirements for Multiterminal systems.

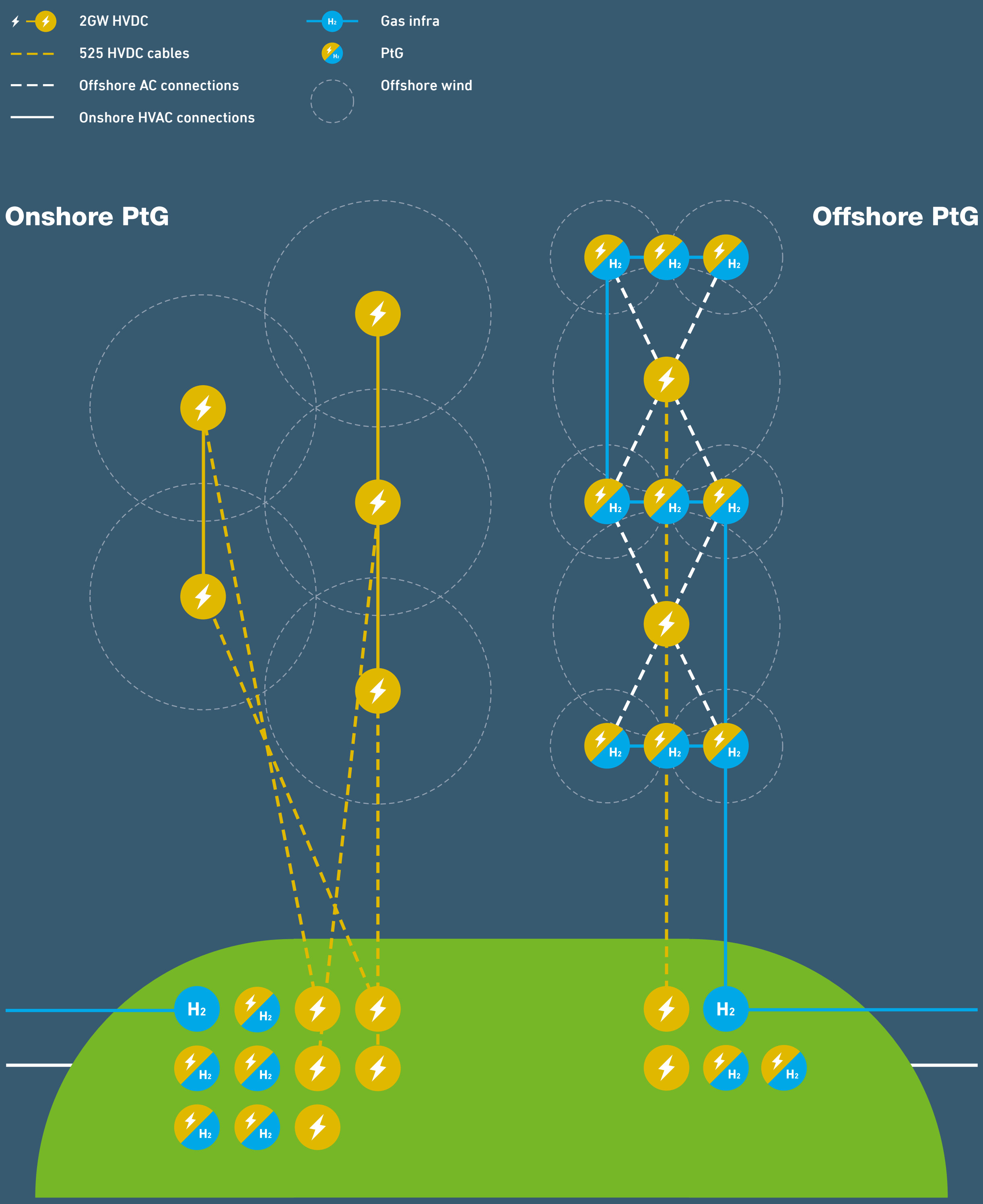
Key message 7

Both onshore and offshore concepts for hydrogen production are technically feasible.

An important feature of the hub-and-spoke concept is the deployment of power-to-gas. The case study for the NSWPH includes 4 GW of electrolysis capacity to provide flexibility in delivering energy to the onshore system. Both onshore as well as offshore electrolysis are considered as an option. Offshore electrolysis has not reached technical maturity yet, as existing offshore electrolysis projects have not yet surpassed the demonstration phase. Even onshore electrolysis has not been proven at a scale beyond a couple of hundred megawatts. We show that both onshore as well as offshore electrolysis are technically feasible at multiple GW scale, and we present design options for both concepts.

We analysed hydrogen supply options by applying a fair comparison framework to onshore and offshore power-to-gas configurations, with a focus on performance and cost. Results include high level technical designs and costs estimates for an onshore power-to-gas installation, and for a semi-optimised platform-based offshore power-to-gas installation.

Figure 4.3 | Two concepts designed for 4 GW of offshore wind capacity were considered for the analysis: On the left, we show 10 GW offshore wind with five 2-GW offshore HVDC platforms and 10 GW power-to-gas onshore. On the right we show two 2-GW offshore HVDC platforms, nine 700-MW offshore power-to-gas platforms and 4 GW of onshore power-to-gas. The total 10 GW system comparison shows that the CAPEX for both configurations is comparable.



The *onshore power-to-gas design* consists of a 4 GW onshore power-to-gas plant. The design includes a single floor, alkaline electrolysis installation matching 4GWe of wind turbine capacity. A compressor station is needed to deliver hydrogen to the Dutch or Danish hydrogen backbone at 60 – 70 bar. The footprint of the total onshore design, including power-to-gas and electrical installations, is estimated to be 95 ha.

The *offshore power-to-gas design* consists of a semi-optimised design for a space-constrained, 4 GW offshore power-to-gas plant. A single offshore power-to-gas installation is based on a float-over platform with dimensions 110x70x40 meters, giving it a footprint of 0.77 ha. The platform includes 500 - 700 MW PEM electrolysis and balance of plant equipment. To achieve the required 4 GW of power-to-gas capacity, multiple platforms are connected by bridge links – the total footprint of the interlinked 4 GW offshore power-to-gas design is estimated to be 4.5 ha.

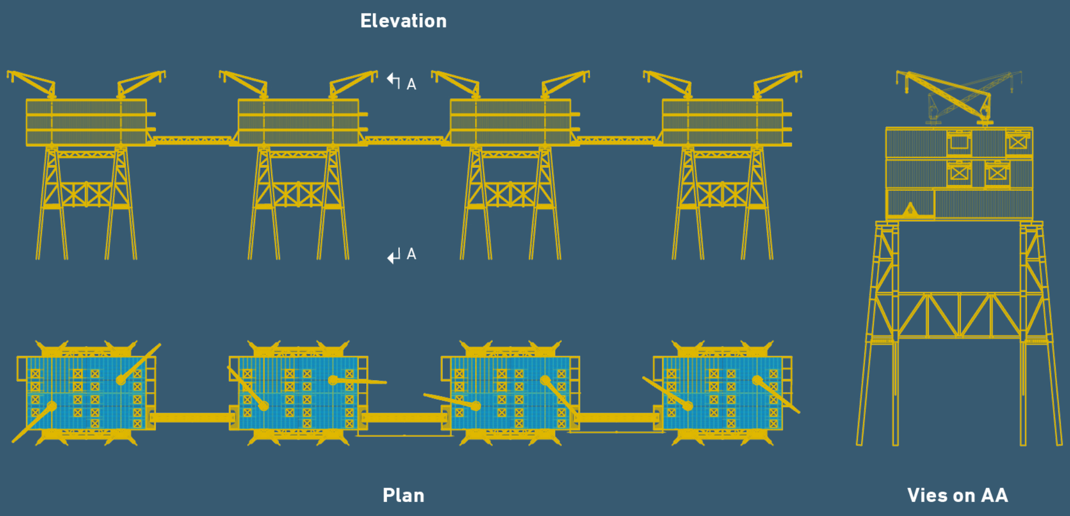
Both onshore and offshore concepts for hydrogen production appear to be technically feasible, with the offshore concept naturally introducing additional challenges such as offshore desalination, and unmanned operation in a demanding environment. The CAPEX of the offshore power-to-gas design is considerably higher than the onshore design. Therefore, the additional cost for offshore power-to-gas needs to be lower than the savings on the electrical infrastructure to make it economically viable.

The offshore power-to-gas platform concept is promising and considered technically feasible. The platform could be an attractive addition to onshore power-to-gas for certain energy transition scenarios, enabling cost-effective offshore modular build-out.

Next Step | The NSWPH consortium will further develop and assess a semi-optimised power-to-gas concept designs for caisson islands as well as grid-integrated hydrogen turbines throughout 2022.

This will enable a detailed comparison across the developed concepts to identify pros and cons for each foundation type and location.

Figure 4.4 | Design of a bridge-linked 2 GW offshore power-to-gas installation consisting of multiple 500 MW power-to-gas platforms.



Key message 8

Repurposing existing pipelines is more cost effective than new pipelines, requiring reclassification to reduce operational risks. New pipelines will carry with them less risk during operation as these will be designed specifically for their intended use.

Power-to-gas is an important aspect of the hub-and-spoke concept; this requires development of hydrogen infrastructure. A hydrogen infrastructure system consists of (a network of) pipelines and compressors. We assessed feasible hydrogen routing options for a particular case study, consisting of either new pipelines or a combination of new and repurposed pipelines for a hydrogen network (see Figure 4.5). The case study considers 6 GW of electric power equivalent hydrogen transport between the Danish energy hub and Danish mainland, 6 GW between the Danish and Dutch hubs, and 12 GW between the Dutch hub and mainland.

One of the challenges is that there are currently no clear design codes for offshore hydrogen pipelines. The most suitable design code for offshore pipelines carrying gaseous, flammable content does not address the specific properties of hydrogen, such as its small molecular size and compatibility with steel materials and welds. Another recognised design code that covers the design of hydrogen pipelines focusses on onshore pipelines, and offshore conditions are not addressed. In our assessment, we combined two design standards to define assumptions on materials, dimensions, coatings, and welds.

Six optional pipeline systems, one system made up of entirely new pipelines and the five others made up of combined new and repurposed pipelines, are identified and assessed. Flow analyses are conducted for the selected route options based on maximum export pressure from energy hubs of 120 bar.

Optimally, a pipeline should be able to accommodate the maximum pressure and resulting hydrogen flow from the selected compressor system, absorb all the pressure fluctuations from the offshore wind-based hydrogen production with minimal need for storage capacity to balance the hydrogen flow, and be suited for line-packing in periods of excess production compared to demand. For new pipelines, this can, to a certain degree, be designed for, but existing pipelines require more attention.

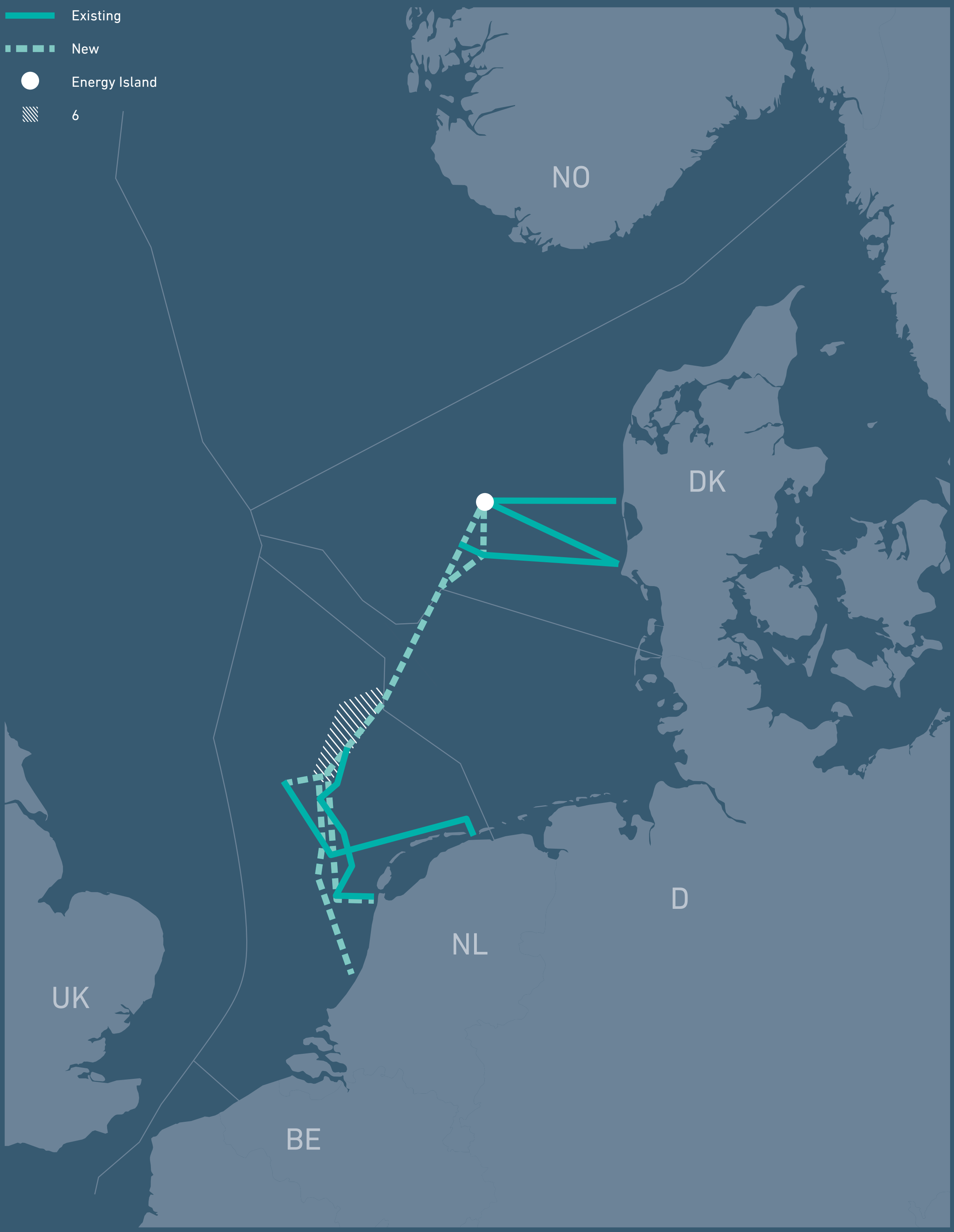
Concepts | Line packing is a method for providing short-term gas storage by compression of gas in a transmission line.

Several risks are associated with repurposing of existing pipelines, the main risk being the uncertain condition of the pipelines, even after take-over of the asset. Mitigation actions include in-line inspections as well as external inspection, resulting in a condition assessment. Also, records from pipeline manufacturing and operation should be retrieved to the largest extent possible. Existing pipelines are more cost effective than new pipelines. However, new pipelines will carry with them less risk during operation as these will be designed specifically for their intended use. The operational flexibility is larger for new pipelines compared to existing pipelines for aspects such as line packing and in withstanding repeated pressure fluctuations.

We conclude that hydrogen pipelines are well suited for transporting energy flow volumes in the order of 6-50 GW (electricity equivalent) per pipeline. Existing infrastructure that satisfies the capacity requirements can be repurposed subject to a requalification program and successful mitigation of identified risks.

Call to action | National governments to provide clarity on landfall locations to allow for detailed pipeline route design, including the assessment of the environmental impact and the criteria to obtain construction permits for new hydrogen pipelines.

Figure 4.5 | Schematic of the project area showing the new (dashed line) and existing (solid line) pipelines that we considered in the feasibility study.



In our assessments, we had to make certain assumptions on which pipelines and corridors are available for hydrogen transport, as well as the design criteria based on multiple design codes. We urge national governments to take concrete steps to provide clarity on pipeline routing options and criteria to obtain permits.

Next Step | Developing operational philosophies that consider the effect of hydrogen production profiles, pressure levels, pressure fluctuations and temperature on the compatibility of the pipeline material with hydrogen.

Including the economics of the possible energy flow(s) and the limits for which the pipeline can be operated without mitigating actions to reduce fatigue crack growths, beyond which inhibitors such as oxygen may be required.

Key message 9

Modular design of offshore energy hubs is preferred to create future flexibility and extendibility. This requires a minimum number of design choices and 5 – 10% of anticipatory investments.

Traditional infrastructure development focusses on single projects bound in space and time. A modular hub development, in contrast, can be expanded over time. This requires anticipatory investments and standardisation in support-, electrical- and hydrogen infrastructure. Not being able to expand a system modular would result in potential higher retrofitting costs, time delays and additional technical challenges to connect systems.

Figure 4.6 | Examples of modular additional substation.

Concepts | Modular design

We define modularity as a feature of offshore hub planning, design, and development that:

- Anticipates future uncertainty and through a level of anticipatory investment minimises the risk to have stranded or sub-optimal assets
- Enables expansion within a hub or through connections to other parts of the North Sea energy system
- Enables discrete expansion steps of sufficiently large size to achieve economies of scale whilst respecting limits imposed due to technology developments and system integration limits
- Tackles dependencies between the different building blocks and functionalities of a hub
- Maintains clearly defined interfaces within a hub or between multiple hubs"

Modularity is needed to *accommodate for future uncertainty* as a hub-and-spoke project enables offshore wind and infrastructure development over a time span of 20-odd years. This includes uncertainties in the scale, location, and timing of offshore windfarm and hub development, as well as system integration and operational aspects.

Another reason for a modular approach is the fact that offshore hubs are expected to evolve over time. This means *expanding* by means of connecting additional offshore wind generation, becoming connected to other hubs or new onshore points, or adding new functionalities such as power-to-gas conversion. The ability of a hub to expand can be either limited or fostered by its initial design.

In addition, all known and foreseeable *dependencies* between the building blocks of a hub should be addressed to enable an offshore energy hub implementation that maximises technical performance benefits and minimises equipment cost of all functionalities that come together in a hub-and-spoke project. These functionalities require specific equipment and infrastructure on the hub and include not only transferring power from an offshore windfarm to shore, but also providing interconnection capacity, managing power flows, converting power to gas, and potentially even storing energy offshore.

Lastly, to ensure compatibility and to enable operation across functions and building blocks, *interface* management is required. Consequently, a successful modular offshore energy hub deployment strongly depends on the degree to which those *interfaces* are defined and properly managed. For example, there must be contractual arrangements to describe the interface between the support structure owner and windfarm operators such that the maintenance personnel of the latter have access to the electrical equipment installed on the support structure for operational purposes. There are also physical interfaces within a hub which require technical standardisation, such as converters, or physical interfaces between different hubs, such as cables. Interoperability between the equipment of different manufacturers is often cited as a major hurdle.

A modular approach when developing an international system of offshore hubs in the North Sea enables discrete expansion steps of sufficiently large size to achieve economies of scale, whilst respecting the limits imposed due to technology developments and system integration limits. We have developed key modular design principles for the regulatory framework, for the support structure, for the electrical infrastructure and for the hydrogen infrastructure. These design principles are:

- *Define the system functionality and system integration principles:* The basis of any modular design is a complete list of functions that a product needs to fulfil, such as power production, transmission, storage, and conversion. These functions are related to and dependent on each other via common system properties.

- *Separate functionalities (transmission, conversion, storage, etc) in distinct building blocks and provide straightforward interfaces between:* Modular design is facilitated by distinct equipment blocks, each designed to deliver its own function. Blocks must be connected via straightforward interfaces, i.e., relatively simple equipment that can be efficiently replaced and tailored to different building blocks.

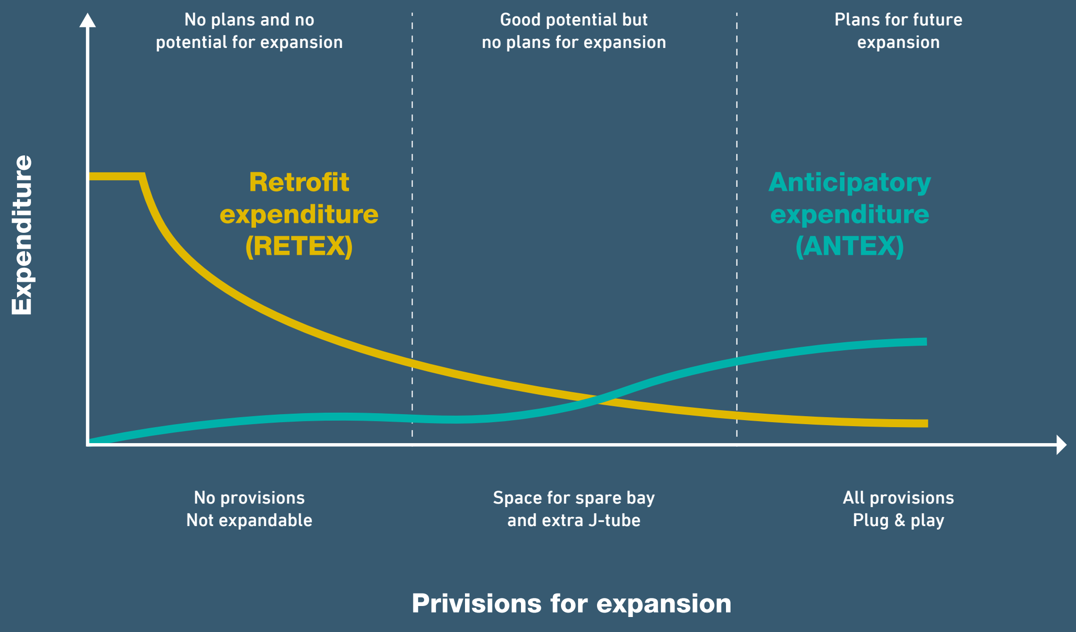
- *Avoid lock-in to specific technology and ensure forward compatibility:* Most products keep developing constantly due to technological progress. A modular design with clear functionalities and well-defined interfaces will make it easier to include future upgrades in offshore energy hubs.

- *Consider potential for expansion and provide anticipatory investment in minimally required interfaces from the beginning to avoid large retrofitting costs in the future:* Relatively small investments can prevent that those future expansions require considerable re-engineering and retrofitting.

- *Consider future space requirements and limitations across all project phases:*Each of the modules, both as a part of the original design and that of future extensions, require certain space for installation, operation, and de-commissioning. In the design of an offshore hub, the physical layout of cables, jack-up positions, etc. should be planned in a way that this allows future extension.

- *Incorporate de-commissioning and replacement procedures in the early design:* Modular design should provide sufficient flexibility towards future changes. Some modules will have to be replaced or removed in favour of new extensions. Potential decommissioning of each of the modules needs to be envisaged in the original design.

Figure 4.7 | Relatively small anticipatory expenditures can prevent that those future expansions require considerable re-engineering and retrofitting expenditures.



Call to action | There is a need to have a sound regulatory basis which would incentivise, remunerate, and regulate anticipatory investments with the goal of creating interfaces for modular growth.

To make expansions of hubs possible beyond their original construction period, it is required to integrate connection interfaces into the original design. The interfaces are needed on electrical and gas infrastructure where there is a potential to create additional connections, as well as on the support structures. Extra space for key enabling equipment must be reserved on hubs to facilitate additional modules and future growth.

Call to action | Call to action: clear ownership, governance and conflict resolution rules for electricity and hydrogen must be in place from the beginning of hub development.

We have assessed existing governance models for offshore wind, transmission infrastructure, and interconnectors and identified a possible governance model for hub-and-spoke projects. This is described in the Regulatory and Market Design chapter. We see the need for clear governance structures for all components of hub-and-spoke projects to facilitate modular design and interface management.

Key message 10

Significant supply chain risks must be addressed for electrolysers, HVDC components and hub foundations.

A hub-and-spoke project encompasses multiple wind farms, hub foundations, and infrastructure corridors. Careful consideration of the supply chain of each of these elements is necessary to identify bottlenecks and enable timely upscaling of (parts of) the supply chain. We have performed a risk assessment on the supply chain for hub-and-spoke concepts, with a special focus on electrolysis, HVDC technologies, and hub foundations.

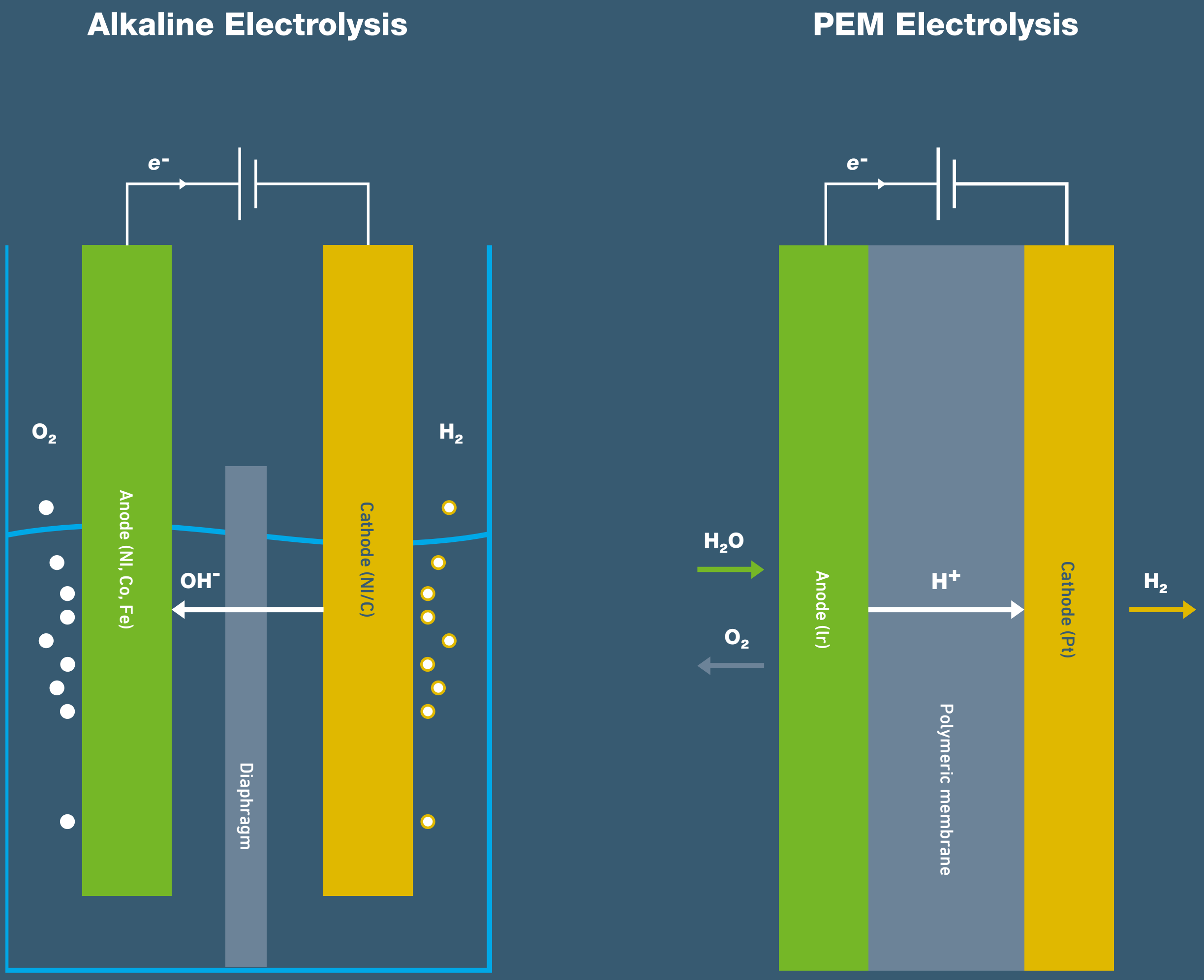
In our assessment of onshore and offshore electrolysis, we propose to use polymer exchange membrane (PEM) electrolysers for offshore applications due to its smaller footprint than alkaline electrolysers. With the current technology generation of PEM, rare earth material use is expected to become a serious issue. The iridium demand for a mature PEM electrolyser market cannot be covered from mine production with current production rates due to the scarcity of the element, its geographical concentration, and coupling of its production rate to the primary platinum group metals. Solutions may include using fewer iridium in new design and re-use of iridium for other appliances.

The current supply chain for electrolyser production faces a challenge to increase the production volume by 2 to 3 orders of magnitude (from tens of MW/a to GW/a) by 2030.The supply chain is currently not well organised in terms of knowledge exchange and product or components standards. This puts a limit to the rate and quality of innovation on the system level as component suppliers have a hard time anticipating on the need of end users and OEMs and vice versa. The lack of performance and safety standards also poses a risk for OEMs and end users when no methods/system of compliance are available to prove compliance to standards.

Both PEM and alkaline electrolysis are well developed technologies, and both technologies are proven to be suitable for continuous production of hydrogen. There is, however, uncertainty in the suitability for intermittent operation. There is shown to be a negative correlation between intermittent operation and stack lifetime. We assessed the performance of electrolyser stacks and systems under variable operating conditions. Results indicate that in terms of long-term stability, PEM electrolysis is well suited for operation with intermittent power sources such as wind or solar.

HVDC converter valves and DC circuit breakers (CB) require a large amount of semi-conductor devices, though nothing compared to competing sectors such as the automotive industry. The rapid rise of the worldwide demand for semiconductors used for power-electronic applications leads to shortages in the supply of switching valves for HVDC converters and DC-Circuit Breakers. This can lead to production delays and cost increase for the NSWPH project. However, observing the actions and investments being taken by the major HVDC

Figure 4.8 | Alkaline electrolysis uses a liquid electrolyte with a porous separator (diaphragm) whereas PEM electrolysis uses a solid membrane and a current to separate hydrogen from water.[IX]



$$4OH^- \rightarrow 2H_2O + 4e^- + O_2$$

$$4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$$

$$2H_2O \rightarrow 4H^+ + 4e^- + O_2$$

$$4H^+ + 4e^- \rightarrow 2H_2$$

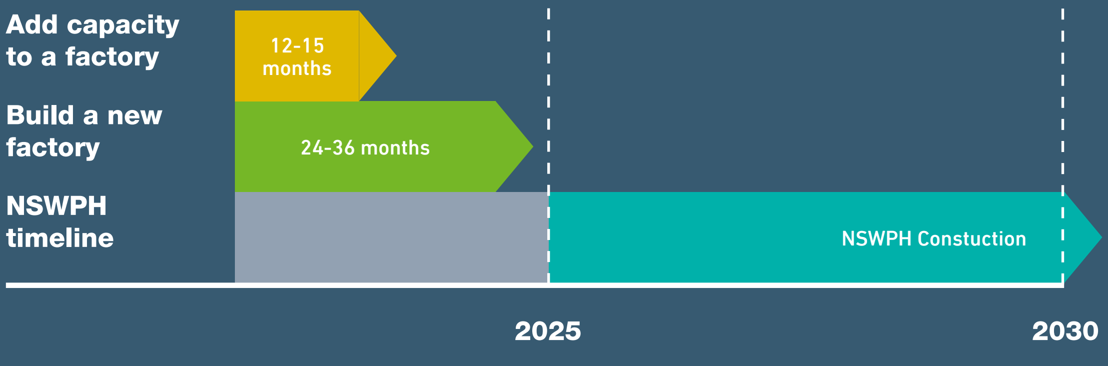
suppliers in Europe and the forecasted lead times of the different solutions, we do not expect the current semiconductor shortage to have impact on the NSPWH construction by 2025 or beyond.

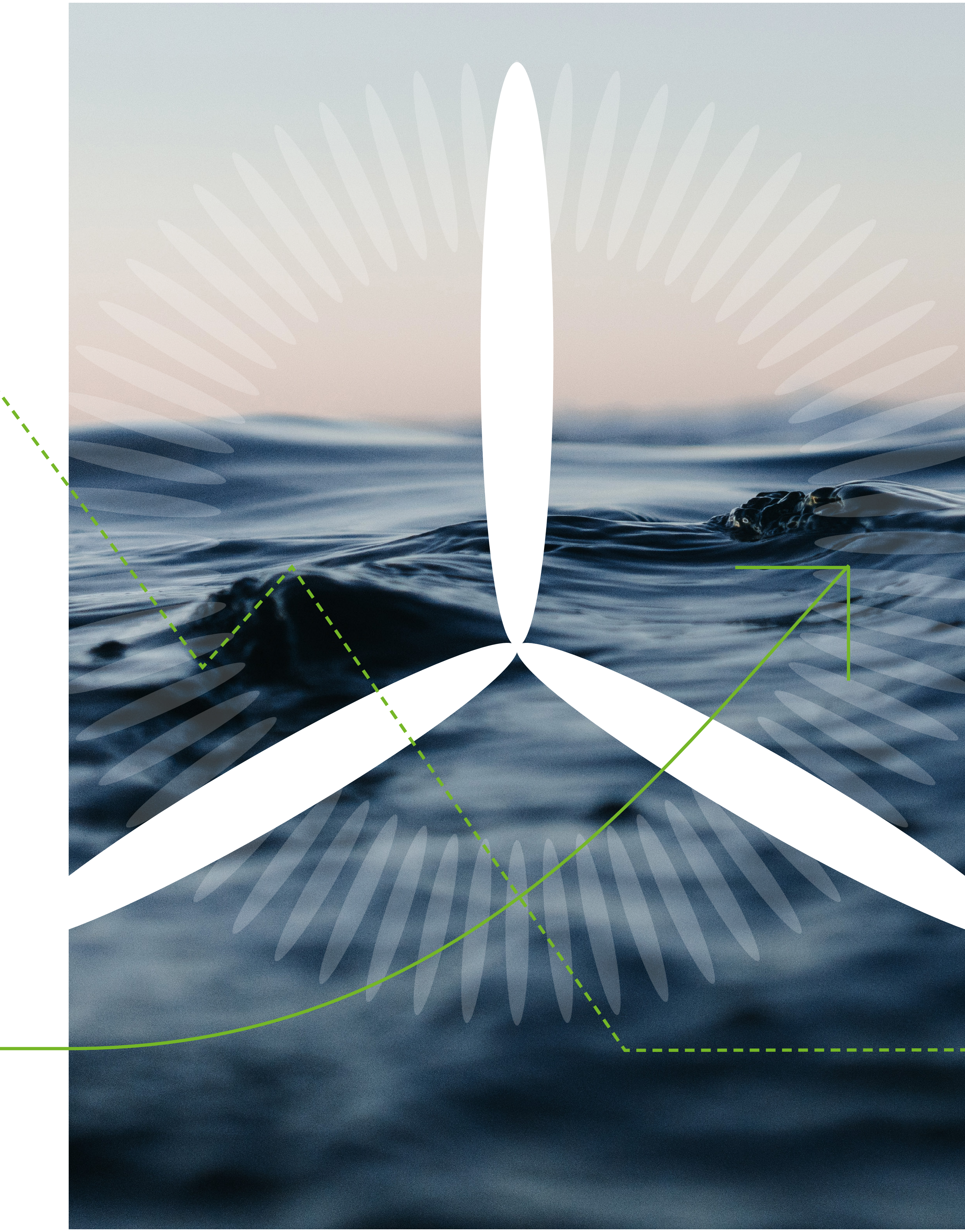
Gas-Insulated Switchgear (GIS) is a well-established and compact solution for both Medium Voltage and High Voltage substations. GIS that is suited for the required HVDC voltage level of 525kV requires SF6 insulation gas. As SF6 is a very strong greenhouse gas, the policy of the NSWPH consortium members is to completely abandon SF6 in new installations. In addition, European regulations might put a ban on the future use of SF6. There is a risk that GIS technology with alternative insulation media will not be available on the market in time. The alternative, Air-Insulated Switchgear, may then have to be applied, which could to a larger footprint of the converter station and related costs. The current regulatory and Technology Readiness Level (TRL) developments into SF6 alternatives do not foster the expectation that the EU will implement any SF6 ban by 2030. An SF6 free solution would most certainly not be available during construction of a hub-and-spoke project before 2030. This means that stakeholders would have to make an exception for NSWPH on their short term SF6 policies and consider replacing the SF6 as alternatives become available. This should be included in the planning and costs of the project in post commissioning phase.

The NSWPH project will employ 525 kV HVDC cable technology. Currently, the highest rated HVDC cable in service is rated at 320 kV, however, ongoing developments have already successfully qualified voltage capabilities up to 525 kV. The consortium members have informed the market on these decisions and are working closely with multiple cable manufacturers in Europe to ensure sufficient supply of this technology at the start of construction timeline. However, the manufacturing of these cables remains to be a specialized characteristic due to the specific knowledge and capital-intensive plants required. Our supply chain assessment showed that present HVDC cable production capacity must increase by 30% to meet the average annual demand between 2025 and 2030.

For the development of caisson-based islands, it is expected that large caissons will be required as preparatory breakwaters, resulting in reduced sensitivity to weather downtime during installation. The supply chain analysis tells us that present day size of caissons is not adequate for waters deeper than 40 meters. The maximum water depth depends on a techno-economic consideration of caisson size and the cost of rock foundations. The overall risk of designing large caissons is considered high, but this can be mitigated by timely (1 year before start of actual construction) EPCI contracting.

Figure 4.9 | Lead times for solutions to the current semiconductor shortage fall within the NSWPH construction timeline.





Cost & Benefits

What have we learned

- ✓ We successfully tested CBA methodologies that we developed for the hub-and-spoke concept and created a stepwise approach to cost-benefit analyses.
- ✓ Deviations from traditional CBA methodologies are necessary to assess the unique characteristics of a hub-and-spoke concept.
- ✓ We identified key drivers for a positive CBA and show that the hub-and-spoke concept is a future-proof way for offshore infrastructure build-out.
- ✓ We need to rethink the traditional one-to-one relationship between offshore wind and transmission capacity, as small amounts of overplanting can improve the CBA outcome significantly.

What will we do next

- We continue to refine the stepwise CBA methodology, with stakeholder engagement as critical element, to assess the costs and benefits of the hub-and-spoke concept. In addition, we will continue to refine energy system and cost data for increased accuracy of the results.
- We continuously will refine our findings on crucial drivers for positive CBAs, including:
  - Overplanting of offshore wind
  - Price of hydrogen imports
  - Electricity- and hydrogen infrastructure buildout
  - Fossil fuel & CO_2 prices
- We will start to execute the stepwise CBA on specific configurations and include stakeholders in the process and inform them on results to support decision-making.
- We will continue to stay informed about other initiatives in the North Sea area, to give the best possible reflection of reality through the CBA. Timely stakeholder consultation is required for alignment and coordination of matters.

Our recommendations

- ✓ We encourage ENTSO-E and ENTSO-G to take an integrated CBA approach as developed by NSWPH to allow for a thorough reflection of the value of an integrated- and mutually reinforcing hydrogen- and electricity infrastructure.
- ✓ In our execution of the stepwise CBA methodology, we will call upon national and European stakeholders to support us as we identified stakeholder consultation as an essential part of a stepwise CBA approach.

Breakthrough

We created a stepwise approach to cost-benefit analyses for the hub-and-spoke concept with stakeholder consultation as an essential element.

A cost-benefit analysis (CBA) is a generally accepted approach for reviewing energy infrastructure projects. Having a CBA is required to provide insights into the relevance of a project and to show decision- and policymakers the added social-economic value of a project. In principle, a CBA is an instrument via which insights can be provided on the wider impact of a project, beyond e.g., the directly involved countries. By providing insights into the project's impact on other EU countries, it enables project stakeholders to enter discussions to utilise EU funds that are meant for exactly this purpose.

The hub-and-spoke concept is different from traditional infrastructure projects for offshore wind and electricity interconnection; in the sense that it is *multinational* in connecting multiple countries and bidding zones, *multi-functional* in combining offshore wind transmission and interconnection, and *multi-energy carrier* in combining electricity and hydrogen production and transport. We have developed a new CBA methodology during the pre-feasibility phase which captures these unique characteristics. In the feasibility phase, we applied the CBA methodology to potential project configurations by means of several CBA studies. In this chapter, we present the lessons learned during this process and initial high-level results.

In addition to determining the costs and benefits of hub-and-spoke project, the Cost and Benefits activity of the NSWPH consortium addresses the allocation of these costs and benefits across cooperating stakeholders. Due to the multinational nature of the hub-and-spoke concept, these costs and benefits are distributed across borders, we therefore refer to this as cross-border cost allocation, or CBCA. This paper will, however, focus on providing an insight into the development and application of an appropriate CBA framework for international, cross-sector hub-and-spoke projects.

Key message 1

We successfully tested a CBA methodology for the hub-and-spoke concept across sectors; both onshore and offshore, and internationally.

Existing CBA guidelines were developed for assessing the socio-economic value of either an electricity or gas infrastructure and storage projects. Therefore, there was a need for the NSWPH consortium to develop a CBA methodology[X] which accommodates the unique features of the hub-and-spoke concept, including hybrid functions of infrastructure elements, energy sector coupling, and multi-national cooperation.

A CBA compares a project (factual) to a reference project alternative (counterfactual). In a previous phase, we have shown that the choice for a counterfactual is not a trivial one. A counterfactual with radial connections to shore, as presented in the Concept Paper of 2021, may require significant onshore grid reinforcements to be able to absorb the offshore wind energy. Such a counterfactual does not provide a realistic reference point for a country where additional onshore reinforcements are unlikely due to, for instance, a relatively low domestic energy demand. For these countries, a counterfactual with limited or no additional offshore wind could prove to be more suitable as the interconnection through a hub-and-spoke concept enables the offshore wind build-out in these countries. For other countries, where radial connections for offshore wind truly are the alternative, this counterfactual does provide the right point of reference. In short, the choice of a suitable counterfactual for a hub-and-spoke concept requires a careful consideration of each countries' reference point.

Concepts | Factual

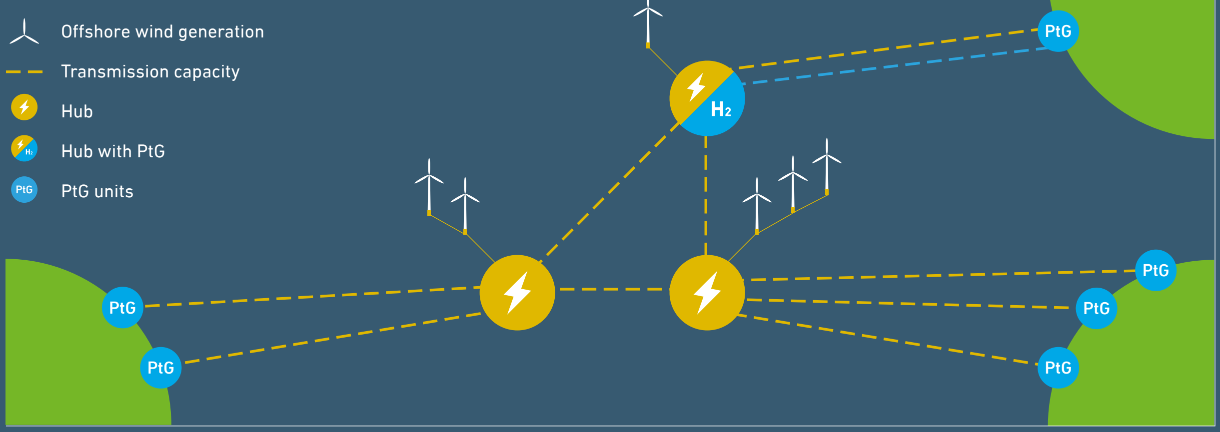
This is the actual project configuration being analysed. In the NSWPH view, this is a possible internationally coordinated and integrated hub-and-spoke project that defines project characteristics in terms of hub structure and size, connection capacities (also between hubs and to shore) and a way of grid integration (e.g., including power-to-gas).

Concepts | Counterfactual

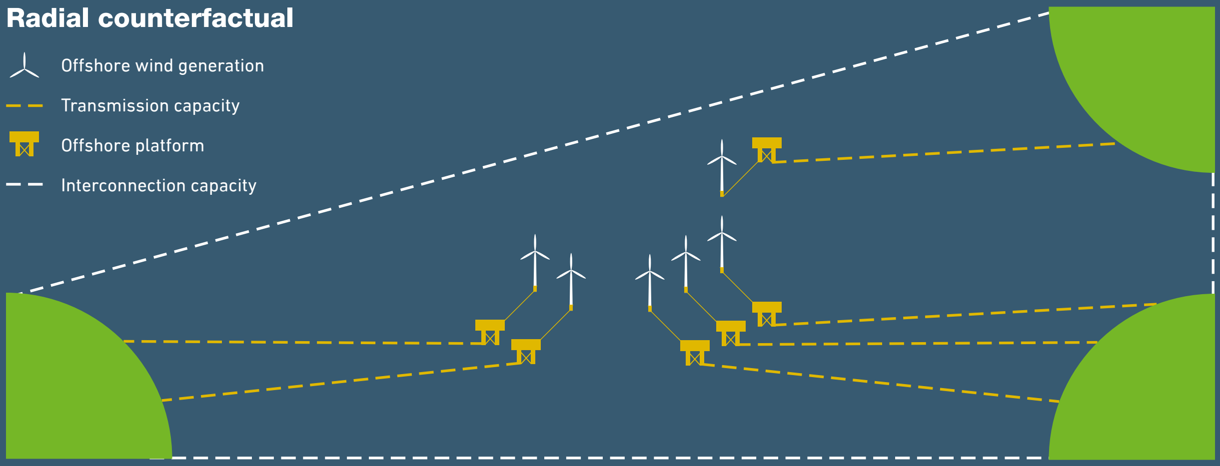
This is the reference case to which the hub-and-spoke project is compared with. It should therefore reflect a less internationally coordinated and less integrated alternative to the factual.

Figure 5.1 | Radial counterfactual is a less internationally coordinated and less integrated alternative to the hub-and-spoke concept where similar levels of offshore wind capacity are connected to the same onshore connection points. The 'empty sea' counterfactual may be applicable, if the hub-and-spoke concept enables the offshore wind build-out and radial connections are not a feasible solution.

Factual

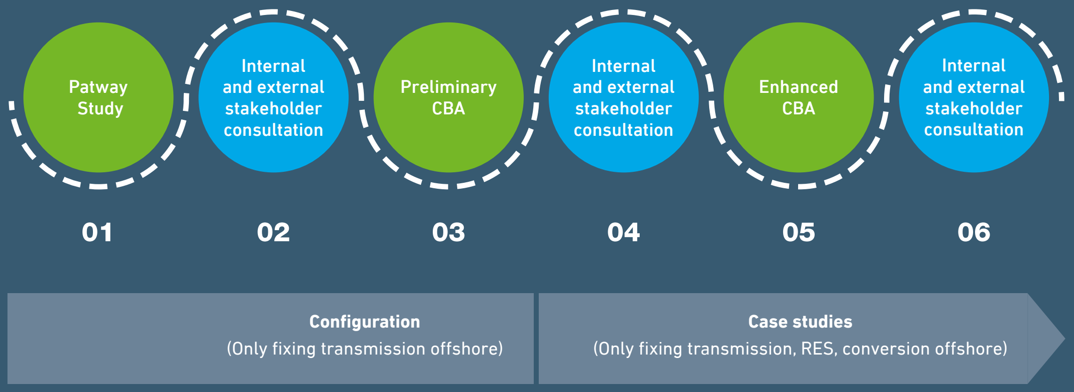


Radial counterfactual



'Emty sea' counterfactual

Figure 5.2 | The stepwise CBA approach created by the NSWPH consortium



In the feasibility phase of the NSWPH project, we successfully applied CBA methodologies developed during the pre-feasibility phase to identify key drivers for a positive hub-and-spoke configuration. These drivers are combined with findings from energy system studies and stakeholder consultation to perform new cost-benefit analysis that also consider optimizing investments and dispatch in the onshore system (on market and technical level) for transmission, conversion, and storage. We learned that a cost-benefit analysis of hub-and-spoke projects benefit from a stepwise approach:

- Identify the drivers of a successful case through subsequent CBA runs. We found that key drivers are the level of offshore wind overplanting, price of hydrogen imports, electricity- and hydrogen infrastructure buildout, and fossil fuel & CO_2 prices.

- Consider learnings from other energy system studies and consult findings with stakeholders. For instance: the Pathways study shows that in a 2050 end-picture, multiple infrastructure corridors in the North Sea prove to be a robust solution for connecting offshore wind farms.

- Perform an innovative chain of cost-benefit analyses with stakeholder consultation as a critical element:
  - Preliminary CBA to evaluate design principles and selected sensitivities of hub-and-spoke projects by assessing their impacts on high-level costs and benefits in the medium term

  - Consult initial findings with internal and external stakeholders: the drivers for a successful case study are discussed within the consortium's organizations and with national governments. The consultation leads to the definition of consensual case studies to take forward.

  - Enhanced CBA methodology for the defined case studies taking into consideration all aspects of a hub-and-spoke project including onshore grid reinforcement requirements

Next Steps | We continue to refine the stepwise CBA methodology, with stakeholder engagement as critical element, to assess the costs and benefits of the hub-and-spoke concept. In addition, we will continue to refine energy system- and cost data for increased accuracy of the results.

Call to action | In our execution of the stepwise CBA methodology, we will call upon national and European stakeholders to support us as we identified stakeholder consultation as an essential part of a stepwise CBA approach.

Key message 2

Deviations from a classical CBA are necessary to assess the hub-and-spoke concept.

CBA guidelines have been developed for transmission infrastructure development projects in the electricity sector ("ENTSO-E Guideline for Cost Benefit Analysis of Grid Development Projects" and its 2nd and 3rd editions) and the gas sector[XI, XII]. These guidelines are enhanced and reviewed every two years under extensive stakeholder consultation and are subject to an official opinion by the Agency for the Cooperation of Energy Regulators (ACER) and approval by the European Commission.

The ENTSO-E and ENTSO-G guidelines are developed primarily for the assessment of conventional investment projects (e.g., a single interconnection cable or pipeline), for single sector projects (only electricity or only gas) and infrastructure or storage projects, not for generation assets or grid connection infrastructure. The hub-and-spoke concept incorporates the features of hybrid assets and energy sector coupling for multiple countries. Given the size of these single sector projects for which the guideline has been established, the impact on investments in the energy system is limited. However, the impact on the surrounding system of a hub-and-spoke project is significantly larger, but these effects are not represented in the conventional CBA.

Concepts | Hybrid infrastructure assets

The term "hybrid projects" as used by the European Commission, North Sea Energy Cooperation, ENTSO-E and Roland Berger, refers to projects in which the development and implementation of Offshore wind and interconnection capacity are combined.

In addition, the ENTSO-E and ENTSO-G guidelines are not suitable to assess the modular nature of the hub-and-spoke concept. Though it may allow for consideration of external developments (such as electricity price development or offshore wind roll-out), additions to the scope of the infrastructural project cannot be well reflected in the CBA. That is, however, very much the nature of the hub-and-spoke concept which allows for step-by-step, or modular development of the project. A CBA methodology for hub and spoke projects requires consideration of the long-term perspective as socio-economic welfare scales with the step-by-step development of infrastructure.

We show that deviations from a conventional CBA are necessary to reflect the costs and benefits of a hub-and-spoke concept. These are summarised in three recommendations.

1. *A case should be modelled in an integrated way*, combining multiple functionalities and energy carriers in a single assessment.

2. For a sufficient net-present value calculation, *the complete timeline of the project should be considered*, including the 2040 and 2050 time horizons, and not only the near future (2030).

3. We need to look at *investments and the surrounding (onshore) system* to show the benefits of an energy hub; as opposed to only considering dispatch, as is the status quo.

In addition, we need to accept a level of uncertainty in the results, given the many assumptions on cost and efficiencies. We, therefore, propose to present and interpret the CBA results within a certain range. Finally, it is important to consider not only the socio-economic outcome of the CBA results, but also the less quantifiable positive effects of the hub-and-spoke concept such as security of supply and system stability.

Next Steps | We will continue to stay informed about other initiatives in the North Sea area, to give the best possible reflection of reality through the CBA. Timely stakeholder consultation is required for alignment and coordination of matters**.**

For instance, ENTSO-E has executed a cost-benefit analysis of the NSWPH project configuration submitted for the Ten Year Network Development Plan (TYNDP)[XIII]. ENTSOE-E concludes that the NSWPH project provides system benefits by optimising integration costs of offshore wind, increasing socio-economic welfare by further coupling energy markets, supporting the security of supply at a wider regional level, and providing potential for innovative power-to-gas concepts to optimise total energy system costs. We look forward to engaging with this and other initiatives to share our findings and learn from best practices.

Call to action | We encourage ENTSO-E and ENTSO-G to take an integrated CBA approach as developed by NSWPH to allow for a thorough reflection of the value of an integrated- and mutually reinforcing hydrogen- and electricity infrastructure.

The stepwise CBA methodology developed by the NSWPH consortium, takes into consideration the unique characteristics of the hub-and-spoke concept. The key learnings are applicable to cross-border infrastructure projects that are envisioned for not only the North Sea, but also other sea basins.

Key message 3

We identified key drivers for a positive CBA and show that the hub-and-spoke concept is a future-proof way for offshore infrastructure build-out.

CBAs were executed for several case studies and energy system scenarios. Our findings include high-level results and important drivers for defining suitable project configurations:

- We found that key drivers are the level of offshore wind overplanting, price of hydrogen imports, electricity- and hydrogen infrastructure buildout, and fossil fuel & CO_2 prices.
- Connecting Danish and Dutch offshore sites shows potential for socio-economic system savings. Additional connections to Norway or the UK can increase the saving potential.
- Onshore infrastructure reinforcement needs are significant. While hub-and-spoke systems seem to alleviate the onshore buildout needs, the high cost of hub-and-spoke offshore infrastructure is not fully compensated by lower onshore infrastructure costs and other benefits.
- The hub-and-spoke concept has a positive integration impact in a system with a high deployment of renewable energy sources.
- Hub interconnections enable more efficient dispatch and savings for necessary investments in the surrounding grid.
- Building offshore wind to the indicated levels as indicated in the Esbjerg Declaration has a positive economic benefit.

Concepts | A case study defines a project configuration in terms of the location of energy hubs and capacities of offshore wind, conversion, and infrastructure capacities. See also Figure 5.2.

Concepts | An energy system scenario defines the energy demand across sectors within the geographical scope and supply capacities of electricity generation. In addition, it includes assumptions on the costs of energy

Key message 4

We need to rethink the traditional one-to-one relationship between offshore wind and transmission capacity as small amounts of overplanting can improve the CBA outcome.

Traditional offshore wind and infrastructure development shows a one-to-one relationship between the capacity of the offshore wind farm and the infrastructure capacity to transport the energy to shore. The cable to shore is designed to be able

Figure 5.3 | Example of what the case studies look like. In this case, the hub-and-spoke concept consists of a distributed hub concept between DK, NL, and DE, and electrical and hydrogen connections between the hubs and their home markets.

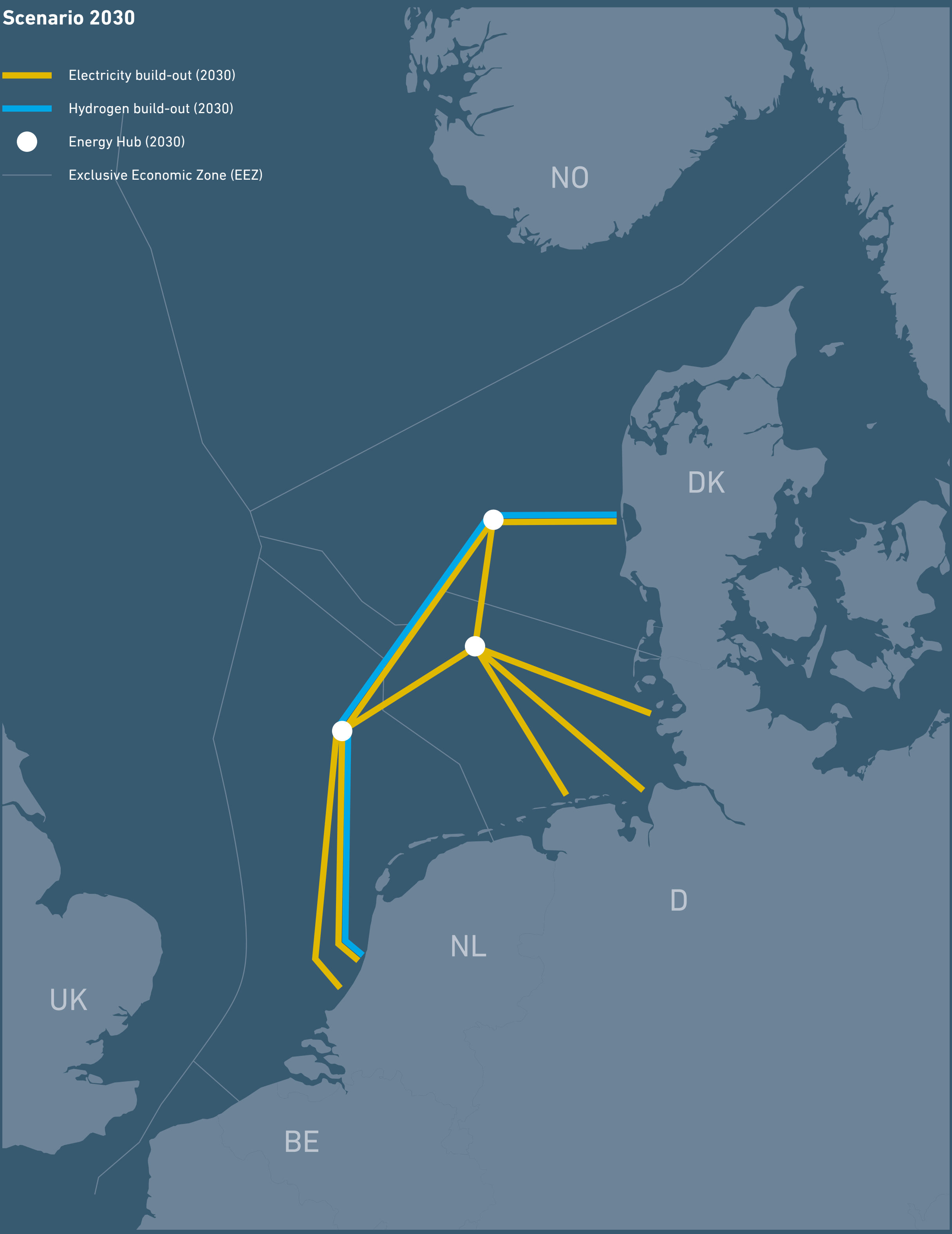
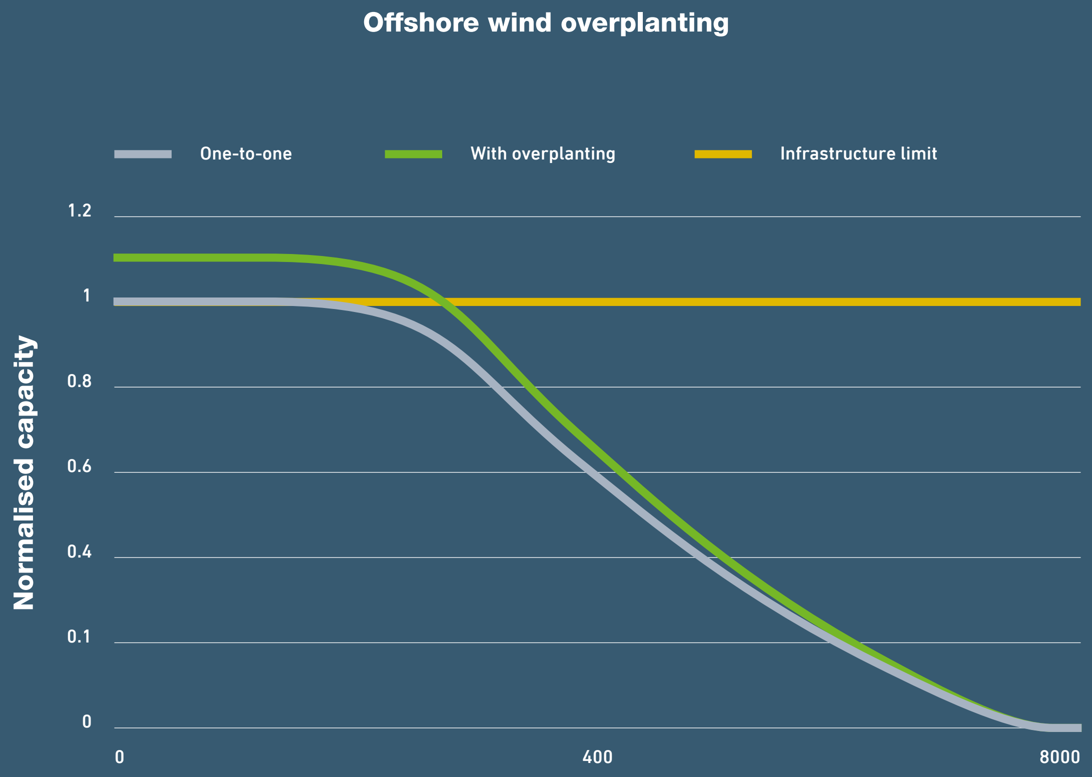


Figure 5.4 | CBA results show maximised socio-economic welfare for a configuration with limited overplanting. This is driven by an increased utilisation of the infrastructure.



to accommodate the peak capacity of the offshore wind farm. In the hub-and-spoke concept, offshore wind energy is accumulated in an offshore hub, from where both cables to shore and interconnectors distribute energy over multiple bidding zones. Given the relatively high cost of electrical infrastructure development, the capacities of cables to shore and interconnectors are carefully aligned with the offshore wind capacity in the definition of case studies. As a rule of thumb, the infrastructure capacity connected to the hub should not exceed the offshore wind capacity of that hub. For the hub-and-spoke concept, the cable to shore is not the only cable connected to the hub and will therefore typically have lower capacity than the offshore wind capacity connected to the hub.

In a cost-benefit analysis with a fixed offshore infrastructure configuration and in which offshore wind capacity has a degree of freedom, the optimal solution shows a minor level of overplanting (10 – 20%). In other words, the hub-and-spoke concept could allow for an increased roll-out of offshore wind. As a result, more offshore wind can be integrated into the energy system at an early phase, without designing the offshore grid for the limited time of peak offshore wind production. Increased production; up to the limit of the infrastructure capacity, results in a better utilization of infrastructure – a key driver in the increased socio-economic welfare.

Concepts | Overplanting

The offshore wind capacity of a hub exceeds the infrastructure capacity of that hub. This results in a higher annual production Offshore wind capacity exceeds the infrastructure capacity resulting in a higher annual production and accepting curtailment of peak production.

Next Steps | Refine the CBA methodology and execute sensitivity analyses.

We will continue to apply the lessons learned to further refine the CBA methodology for the hub-and-spoke concepts. Frequent consultation of- and alignment with stakeholders and initiatives is of importance here to ensuring progress and quality.

Additionally, the initial CBA results are promising in terms of socio-economic welfare caused by overplanting of offshore wind. The consortium will include the key learnings in design choices for further assessments and assess the sensitivity to certain key assumptions, including:

- Overplanting of offshore wind: initial analysis shows promising results for 10 – 20% of offshore wind overplanting. Further assessment is needed to determine the sensitivity to the level of overplanting in the system.

- Price of hydrogen imports: we need to understand the competitive position of domestic hydrogen production in reference to hydrogen import prices.

- Electricity- and hydrogen infrastructure buildout: though we've very carefully defined cost figures, recent supply chain issues and raw material prices call for additional analyses for CAPEX levels.

- Fossil fuel & CO_2 prices: the price of fuels for conventional dispatchable power plants impact the value of renewable electricity and hydrogen in the energy system of northwest Europe.

Regulatory & Market Design

What have we learned

- Offshore bidding zones are more robust in providing socio-economic benefits compared to the home market setup and provide more efficient locational and dispatch incentives to offshore load as e.g., electrolysers.
- An alternative approach to the bidding zone review process by following article 14(7) within the existing Electricity Regulation can reduce the time to reach a final bidding zone decision from 20 – 34 months to 9 – 18 months.
- A suitable governance model for hub-and-spoke projects divides system planning, ownership, and operation between national TSOs, HNOs, state-owned entities, and commercial parties.
- Financing and cost recovery of hub-and-spoke projects can be largely covered by existing national financial and economic frameworks.

What will we do next

- Assess electricity system balancing in an offshore bidding zone setup and draft recommendations towards policy makers.
- Assess how risks change for OWFs and electrolysers when being part of an energy hub under an OBZ setup, potential mitigation schemes and draft recommendations towards policymakers.
- Continue to support national governments in their decision making on regulatory, market and legal aspects of offshore infrastructure development.
- We will further analyse the regulatory framework regarding hydrogen, which is currently being developed, and its impact on governance models and stakeholders.

Our recommendations

- Policymakers decide on the approach to establish an offshore bidding zone and that the European Commission adopts a position on the approach to establish an OBZ.
- National governing bodies decide on new aspects such as the (offshore) hydrogen infrastructure, hub foundation, system planning responsibility and interconnectors between national hubs.
- National governments provide clarity on the financial and economic frameworks of the hub foundation, suitability of the Dutch offshore grid framework for energy hub concepts and on regarding anticipatory investments.

Breakthrough

Offshore bidding zones are more robust in providing socio-economic benefits compared to the home market setup and provide more efficient locational and dispatch incentives to offshore load as e.g., electrolysers. We show that the implementation of offshore bidding zones can be realised in 9 – 18 months.

The multinational and multifunctional nature of the hub-and-spoke concept requires a careful assessment of the regulatory and market design frameworks in all the countries of relevance as well as on a European level. We have identified key principles for market design, governance models, and financial and economic frameworks within which the hub-and-spoke concept can be developed.

Key message 1

Offshore bidding zones are more robust in providing socio-economic benefits compared to the home market setup and provide more efficient locational and dispatch incentives to offshore demand such as electrolysers.

The main difference between home market and offshore bidding zone (OBZ) setups is the allocation of income over the stakeholders. Where under the home market setup, higher revenues and thus income is received by the offshore wind farm operators, this income under the OBZ setup might be redistributed in the form of congestion rents. Even so, the offshore bidding zone market setup proves to be more robust in providing socio-economic welfare than the home market setup. The OBZ setup is more future-proofed to cope with a large up-scale of offshore projects since it does not require counteractions of the TSOs to deal with congestion due to the 70% rule. Furthermore, the OBZ gives price signals which efficiently incentivise demand such as power-to-x assets to locate near electricity supply and dispatch at moments when the produced electricity is green. The effect will likely to be increased by the Delegated Act to RED II, proposed in May 2022, that provides for the requirements of green hydrogen. Hydrogen produced in a bidding zone with more than 90% renewable electricity is considered green hydrogen.

This conclusion is in line with the European Commission's position on the market setup. It is the Commission's view that establishing offshore bidding zones provides a good approach to ensure compliance with the cross-border trading rules and to allow the energy to flow to where it is most needed. In addition, offshore bidding zones achieve a higher degree of overall efficiency than the 'home zone' approach"[XIV]. This is in line with the opinion of ENTSO-E which already uses offshore bidding zones as the working assumption in e.g., the Ten Year Network Development Plan (TYNDP). Also, ACER and CEER recently expressed their preference for OBZs in their reflection on the offshore renewable energy strategy[XV].

Concepts | Home Market Setup and Offshore Bidding Zone Market Setup

In the home market setup, the offshore wind farm bids and dispatches into its home market and receives the home market electricity price. The cable from the hub to shore is an internal transmission asset, whereas the cables between the hubs in their respective home markets are cross-border interconnectors. In the offshore bidding zone setup, the hub forms a separate offshore zone, in which the offshore wind farms submit bids that are dispatched. Via market coupling the offshore generation is matched with onshore demand. The electricity price within the offshore bidding zone is the result of market coupling.

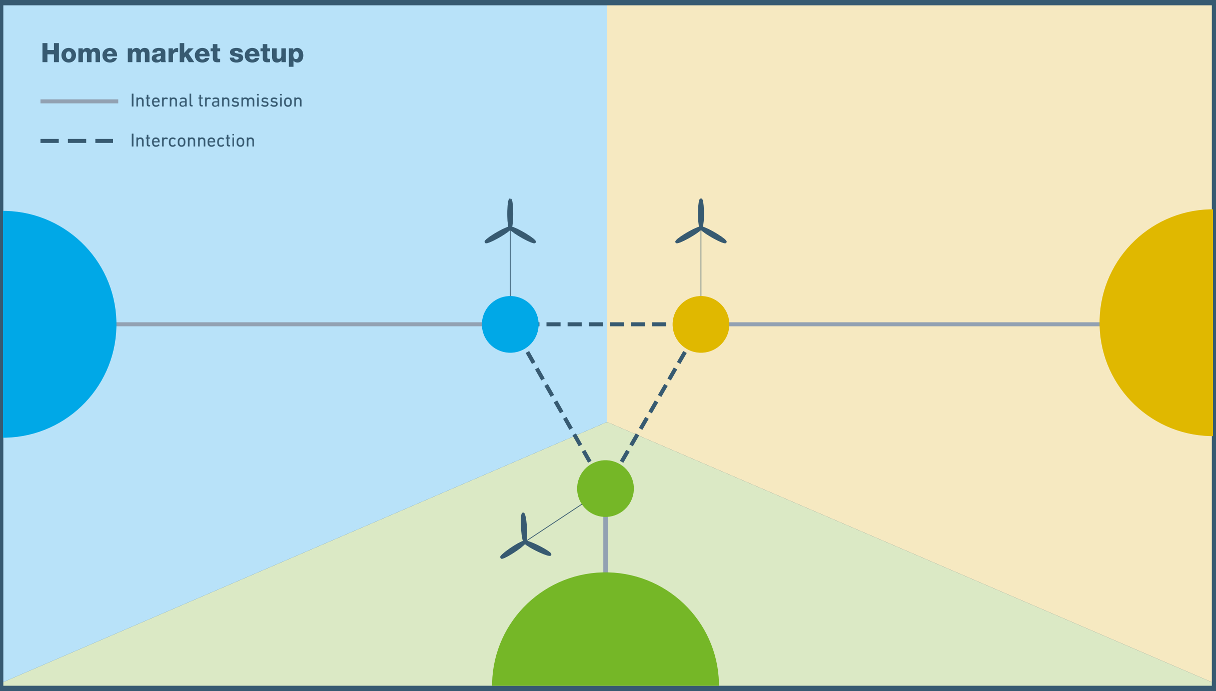
In the OBZ setup, all cables between the hubs and from the hub-to-shore are interconnectors. In this way, the OBZ setup complies with the 70% rule, which requires that on all bidding zone borders, at any point in time, 70% of the capacity must be made available for cross-border electricity trading. The home market setup does not necessarily comply with this rule. There are three ways to let the home market setup comply with the 70% rule:

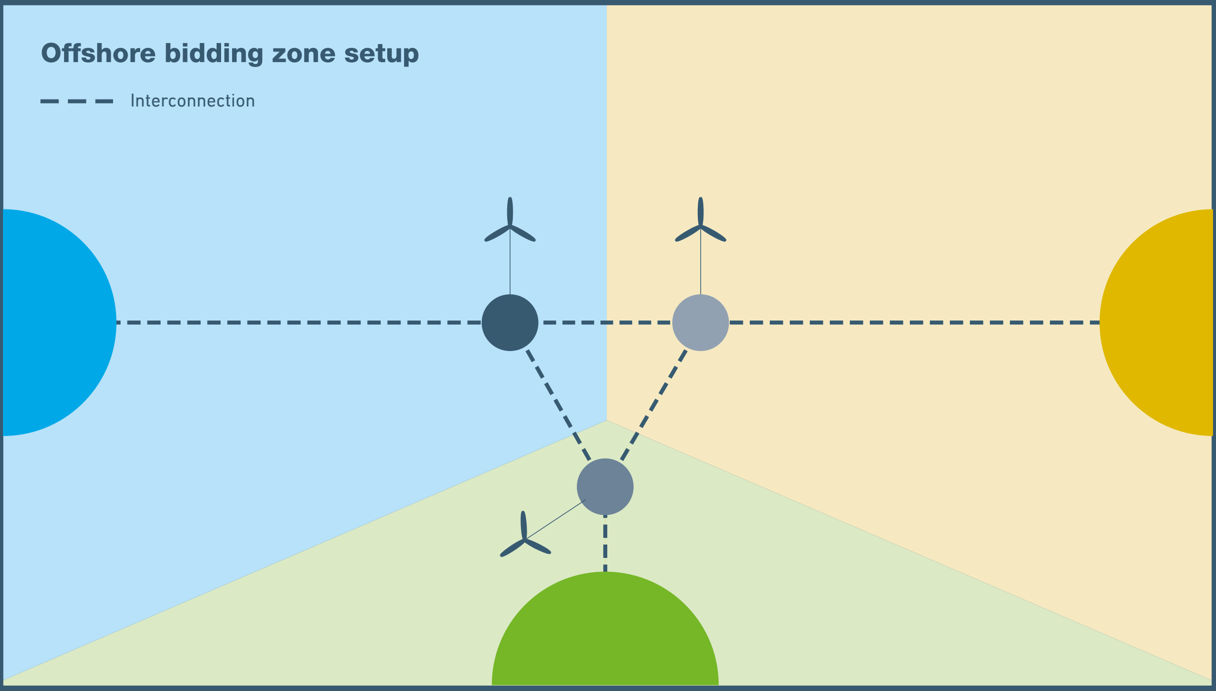
1. Over-dimensioning of the cable which reduces the cost efficiency aspect of a hybrid project,

2. Allowing structural congestion and therefore costly curtailment or countertrading counteractions by the TSO, or

3. An exemption from the 70% rule or change of regulation of the 70% rule and the rules regarding priority access. This results in a risk of non-compliance with to the principle of non-discrimination.

Figure 6.1 | In the home market setup, each hub is part of the home market bidding zone. The connections between hubs are interconnectors, whereas the cables to shore are transmission cables. In the offshore bidding zone market setup, each hub is its own bidding zone. Each cable is therefore an interconnector.





Over-dimensioning the transmission cable or, alternatively, curtailment of offshore wind is economically inefficient and undesirable.

We have shown that the offshore bidding zone setup results in marginally more efficient dispatch and capacity allocation for two configurations, demonstrated by increased flows towards high-priced bidding zones. The offshore bidding zone setup results in more socio-economic welfare compared to the home market setup when a wind forecast reliability margin is included in the modelling. This effect is increased when countries with less correlated electricity markets are included in the project. Therefore, the offshore bidding zone is more robust in providing socio-economic welfare.

Key message 2

We propose an alternative approach to the bidding zone review process within the existing Electricity Regulation to reach a final bidding zone decision between 9 – 18 months.

Bidding zone borders are based on long-term structural congestion in the transmission network. Establishing a new bidding zone, be that within Member States' borders or a new, offshore bidding zone, requires an analysis and identification of structural congestion. The bidding zone review process is anchored in the Electricity Regulation[XVI] and the Capacity Allocation and Congestion Management (CACM) Guideline[XVII].

The main barrier in the current bidding zone review process is the discrepancy between the lead time of *hybrid projects* (see Cost and Benefits) and the review process. Tendering of offshore wind farms for hybrid projects takes place about 5 – 7 years ahead of operation. This means that clarity on market design, regulatory and legal framework is required even before that moment. The bidding zone review process based on the Electricity Regulation includes infrastructure projects planned for the coming three years. Within the current regulation, projects with a horizon beyond three years cannot be included in the review process. As a result of the lead time for hub-and-spoke projects, it is impossible to provide clarity on the market setup before tendering of offshore wind farms.

Another barrier is that the bidding zone review is a lengthy and cumbersome process with multiple actors and stakeholders. When structural congestion is identified, TSOs are to prepare an assessment methodology and propose alternative bidding zone configurations. The alternative configurations must be approved by the relevant National Regulatory Authorities (NRAs) by unanimous decision, or by ACER in case of non-unanimous decision. After the TSOs assess the configurations, a consultation round is initiated by the TSOs – an important feature, but also one that provides uncertainty regarding timeline and outcome of the bidding zone review process. Final approval by member states or the European Commission is required before a decision on implementation is taken. The overall process takes between 20 – 34 months.

Finally, the bidding zone review process is mainly focussed on the existing onshore bidding zones. For instance, the technical report referenced by the CACM Guideline is based on a substantial amount of historical data describing congestions within existing, onshore bidding zones. Such data is not (yet) available for newly considered offshore bidding zones. On top of that requires the bidding zone review process to studya set of 22 indicators, which are all relevant in the context of reviewing and potentially amending the existing configuration, but are not all relevant for determining the optimal configuration for a future hybrid project. Finally, the BZR includes an assessment on the removal of congestion by analysing and assessing new configurations of bidding zones. This seems not relevant to hybrid projects under an OBZ setup as this is done by creating a new bidding zone in the first place, based on already expected and foreseen structural, long-term congestion.

As discussed above,t hybrid projects exhibit by definition structural congestion in case the infrastructure elements are not over-dimensioned.

Figure 6.2 | The establishment of a separate bidding zone is one of the various steps that must be followed to realise an offshore hybrid project. Creating a regulatory and legal framework is estimated to take approximately three years. With the current view on timeline regarding the establishment of an OBZ, this leaves a time window for decision making to about five years before the tender for the OWF takes place.

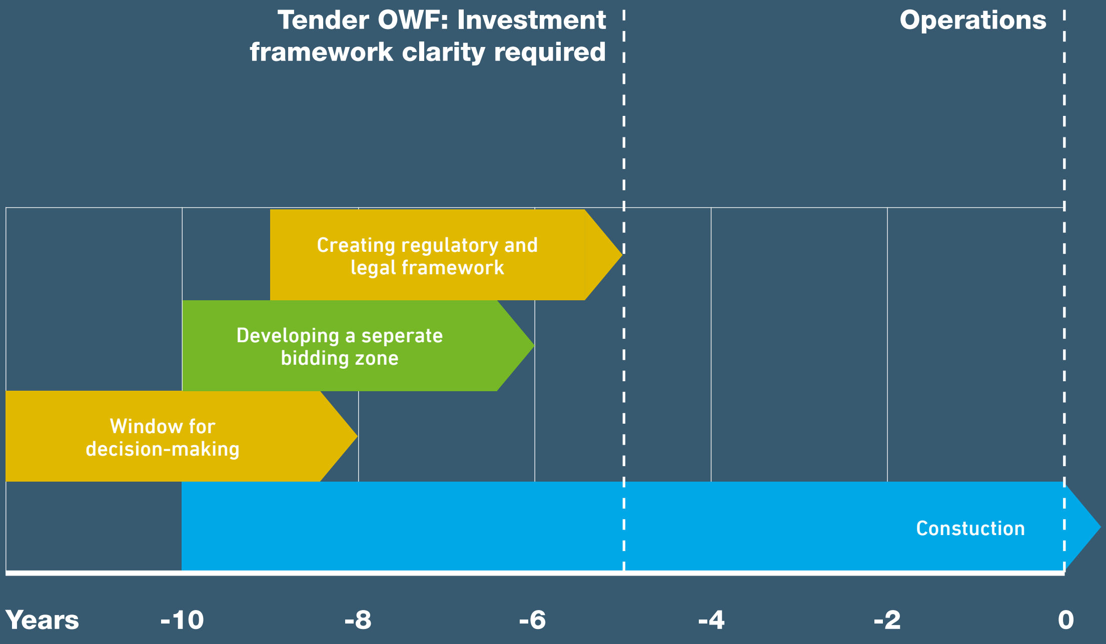


Figure 6.3 | Article 32 of the CACM Guideline provides a comprehensive description of the bidding zone review process. The overall process can take up to 34 months[1].

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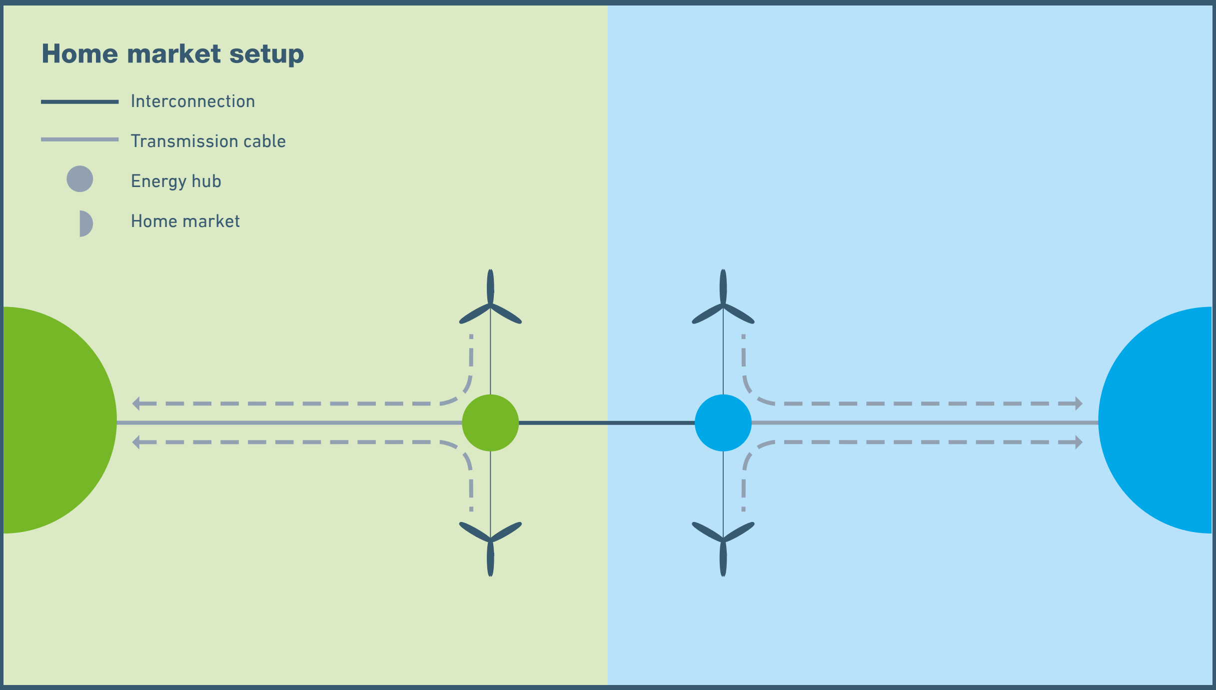
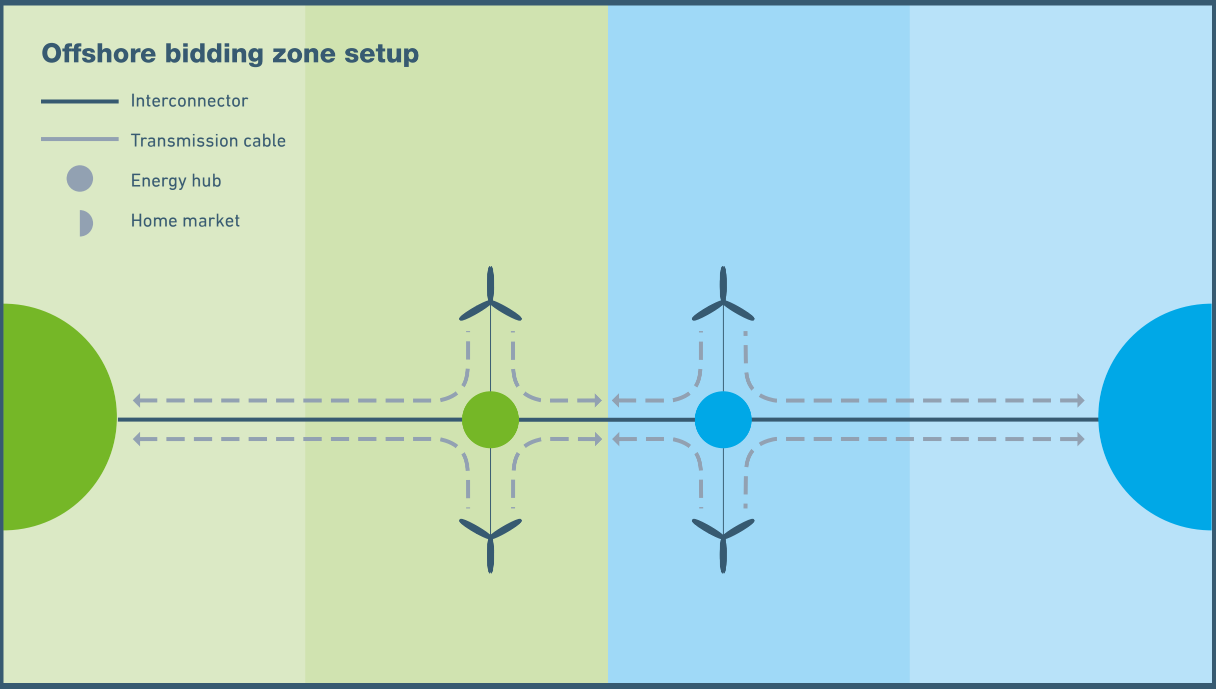
[1] Note that the 4-month process for TSO(s) to prepare alternative bidding zone configuration is a high-level assumption.

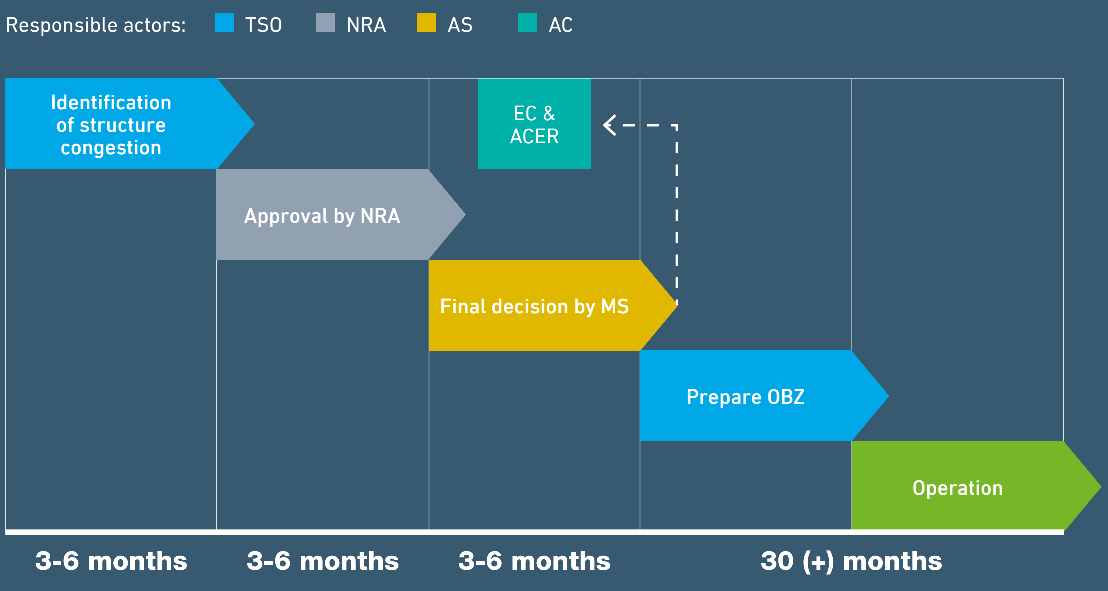
Figure 6.4 | In the home market setup, the home market connections can, after subtraction of 70% of the cable capacity for interconnection flows, only use 30% of the capacity to transport wind energy flows. In case the cables to shore are not over-dimensioned, this will result in structural congestion on the hub-to-shore cables. The alternatives are to either increase the capacity of the transmission cables, structurally curtail offshore wind, or initiate a bidding zone review. In an OBZ, the bidding zone borders reflect the structural congestion.





This is because interconnection and offshore wind transmission flows need to be co-optimised. The ‘70%-rule’ in the Electricity Regulation, states that TSOs can not unduly limit the interconnection capacity for cross zonal trade below 70% of the capacity. In hybrid projects under a home market setup, the home market connections can after subtraction of 70% of the cable capacity for interconnection flows, only use 30% of the capacity to transport wind energy flows. In case the cables to shore are not over-dimensioned, this will result in structural congestion. TSOs cannot limit the available capacity of the interconnector beyond 70%. Therefore, the structural congestion on the transmission cable warrants a bidding zone review (see Figure 6 4).

Figure 6.5 | An alternative approach to the bidding zone review based on the principles of the Electricity Regulation.



Alternatively, the Consortium identifies an alternative approach that enables a swift bidding zone implementation within existing regulatory frameworks. Following the principles of the Electricity Regulation, by default bidding zone borders need to be applied to deal with these structural congestions on the network elements. This leads to the creation of an OBZ for the offshore hub and all HVDC cables between the hub and the onshore grid become bidding zone borders. To establish an OBZ for the offshore hub in principle it should suffice to justify that all network elements between the hub and existing bidding zones contain structural congestion, and that there is no need to execute a full bidding zone review process. To identify the structural congestion, a technical report should be drafted, pursuant to option three of Electricity Regulation article 14-(7), by the TSO responsible for providing grid connection to the project. After approval on the technical report, the relevant MS shall make the decision to establish a (new) OBZ. The whole process could take somewhere between 9 – 18 months, significantly faster than the current 20 – 34 months.

Call to action | For the short term, we recommend that policymakers decide on the approach to establish an OBZ and that the European Commission adopts a position on the approach to establish an OBZ.

In case the Member States prefer an OBZ market setup, it is recommended to soon take a decision on which implementation approach should be followed. The alternative approach takes approximately 9 - 18 months and a bidding zone review can take up 20-34 months or even longer in case of delays. It is crucial for investors to have a clear view on the market setup as they require this to enable a clear, calculable investment case.

It may be crucial to obtain a clear statement regarding the approach to establish an OBZ by the European Commission to prevent Member States to all start formulating their own approach. A standardised approach is necessary to integrate the fast-growing amount of offshore wind for the coming decade in a cost-efficient manner through hybrid projects.

Key message 3

We identified a suitable governance model for hub-and-spoke projects that divides system planning, ownership, and operation between national TSOs, state-owned entities, and commercial parties.

Major developments that have taken place since September 2021 and that have a significant impact on the Hub-and-Spoke Projects developed by North Sea Wind Power Hub are not reflected. One of these major developments is the publication by the European Commission of the EU framework to decarbonise gas markets, promote hydrogen and reduce methane emissions on 15 December 2021. The publication of this draft and the subsequent legislative process provide an outlook into the future roles and responsibilities of the various participants on the hydrogen market, both onshore and offshore.

Concept | A governance model describes the roles and responsibilities of stakeholders throughout the lifetime of an asset, or system of assets.

The hub-and-spoke concept combines a hub foundation, electricity and hydrogen infrastructure, and the functions interconnection and offshore wind energy transport in a single project. These unique complexities call for re-assessment of existing governance models. Existing governance models for offshore wind, interconnectors, and natural gas transmission are assessed for Denmark, the Netherlands, Germany, and the United Kingdom. In addition, national and European governance trends in offshore wind and infrastructure development are identified.

The governance model assessment focusses on three building blocks of a governance model: planning, asset ownership and system operation. The *planning* block describes the responsibility for system planning, including scenarios on future energy production and usage, and implications for further infrastructure investments. *Asset ownership* describes who is the majority owner of the assets within the system; This responsibility typically includes pre-development, development, and construction. *System operation* relates to coordination of the system once it is operational, including operational planning, system, and markets operations[2], and post operational tasks.

Concept | In a centralised governance model, system planning, ownership and operation is assigned to a national entity, usually a TSO and/or HNO. In a decentralised governance model, ownership of infrastructure assets is attained by a commercial entity.

Figure 6.6 | A suitable governance model for hub-and-spoke projects divides system planning, ownership, and operation between national TSOs, Hydrogen Network Operators (HNOs) state-owned entities, and commercial parties.

	Reference model	
Planing	System planning	Consortium of TSOs
Ownership	Hub foundation	National electricity TSO and/or gas TSO/national state-owned entity
	Offshore transmission cables (hub to shore)	National electricity TSO
	Interconnector cables (hub to hub or hub to foreign shore)	Consortium of electricity TSOs
	Hydrogen transmission pipelines	National gas HNO's
	Offshore storage or PtG assets	Privately owned (commercial developers)
System operation	System operation	National TSOs

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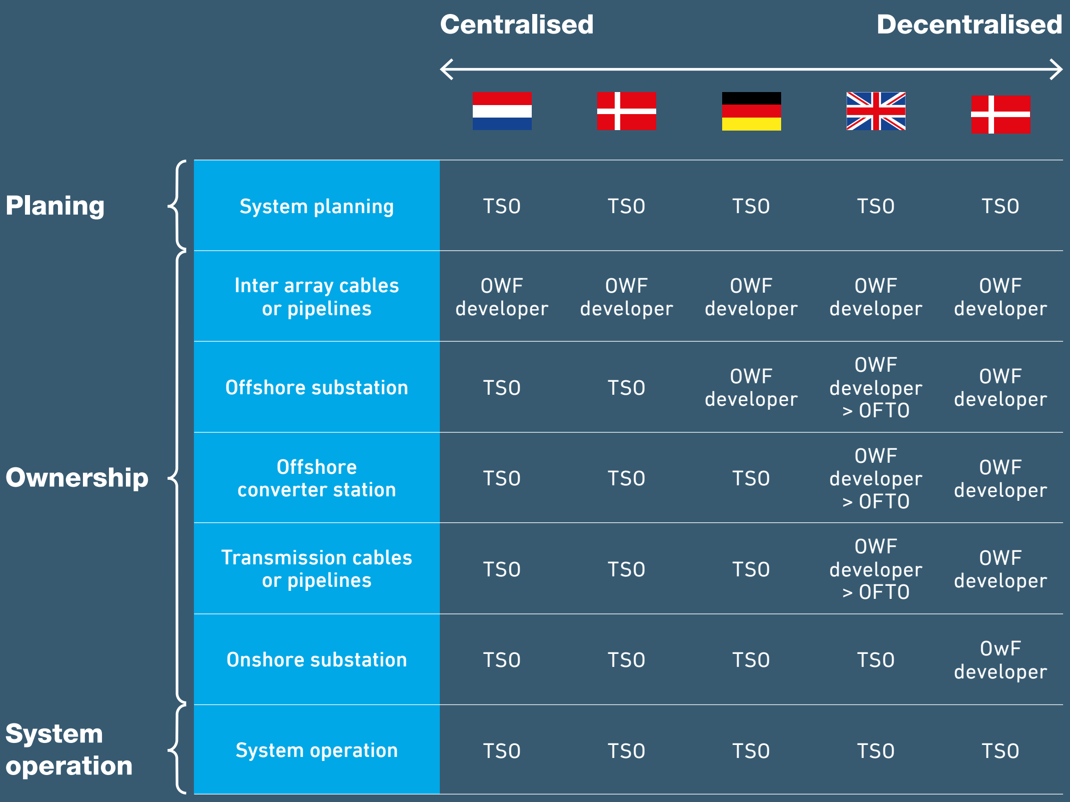
[2] Note that market operation is done by nominated electricity market operators such as, for instance, EPEX Spot in the Netherlands. Market operation is therefore not included in the scope of this assessment.

Interconnectors are cross-border power lines, allowing for electricity exchanges between markets, and thus providing enhanced security of supply for each of the interconnected markets. Given the multi-national nature of interconnection, governance of assets is subject to various regulatory regimes. Typically, the applied regulatory regime is a negotiated outcome between the relevant TSO's, Member States and national regulatory authorities (NRA). That means that an interconnector is exposed to two NRAs, and associated costs are often allocated on a 50-50% basis. Europe knows two types of interconnectors ownership models: fully regulated and partially regulated (merchant). The former is most common in continental Europe, whereas the latter is most notably used in the UK.

Figure 6.7 | Overview of existing governance models for offshore wind development. Where some countries favour a centralised governance model for infrastructure development (e.g., Germany and the Netherlands), other countries prefer decentralised (e.g. .UK).



		🇳🇱	🇩🇰	🇩🇪	🇬🇧	🇩🇰
Planing	System planning	TSO	TSO	TSO	TSO	TSO
Ownership	Inter array cables or pipelines	OWF developer	OWF developer	OWF developer	OWF developer	OWF developer
	Offshore substation	TSO	TSO	OWF developer	OWF developer > OFTO	OWF developer
	Offshore converter station	TSO	TSO	TSO	OWF developer > OFTO	OWF developer
	Transmission cables or pipelines	TSO	TSO	TSO	OWF developer > OFTO	OWF developer
	Onshore substation	TSO	TSO	TSO	TSO	OwF developer
System operation	System operation	TSO	TSO	TSO	TSO	TSO

Concept | In a fully regulated interconnector governance model, interconnection assets are part of the regulated asset base and therefore rely on a regulated income. Its main investment objective in the regulated governance model is to maximise social welfare. TSOs earn a regulated revenue through network charges, based on the cost of the development and operation of assets. An interconnection under a merchant governance model relies on a market-based income, obtained through congestion rents, and its main investment incentive is to maximise private profits through the collection of congestion rents, while there are benefits to social welfare as well. Governance of natural gas transmission in Europe resembles that of electricity transmission. For onshore natural gas infrastructure, the gas-TSO is responsible for planning, ownership, and operation of gas transmission assets.

Note that in several Member States, commercial operators can own and operate offshore natural gas pipelines with third party access. For interconnection of natural gas throughout Europe, national TSOs of the respective countries are responsible for planning, ownership, and operation of the assets. Like electricity interconnection, cost is allocated to the respective TSOs based on mutual agreements between the TSOs, Member States and NRAs. Note that an interconnector can also be owned and operated by non-national TSO's, such as the BBL pipeline from the Netherlands to Great Britain. This requires an exemption from the tariff regulation under EU law, so the tariffs are negotiated between the pipeline operator and its customers.

On a European level, several new policies may impact governance of infrastructure projects. *The Offshore Renewable Energy Strategy* specifically notes integrated planning and development as a priority. *The Staff Working Document* on the *Offshore Renewable Energy Strategy* further assesses the implications of future development options and unbundling of the energy market. The revised TEN-E regulation endorses integrated grid planning and development and outlines the necessary next steps. On a European level, the revised regulation calls for an enhanced role for the European Commission and ACER to oversee the Ten-Year Network Development Plans. On a national level, the revised TEN-E outlines changes to permitting procedures and emphasises the need for a coordinated permitting procedure to ensure efficiency and enable investor certainty. *The EU Hydrogen Strategy* emphasises the need for full integration of hydrogen infrastructure in infrastructure planning. While none of these publications clearly and undeniably endorses a centralised model over a decentralised model, the emphasis on integrated grid planning and strong oversight by the European Commission and ACER indicate the desire for national and European coordination in grid planning and development. Even more recently, the *legislative proposal to recast the 2009 EU Gas Directive* states that a Hydrogen Network Operator (HNO) must be assigned by member states.

While a wide variety of governance models is possible, the NSWPH consortium provides an example of a governance model by extending the currently applied governance models in the relevant countries. A governance model for hub-and-spoke-projects based on existing governance models for offshore wind transmission and interconnection allows for enhanced speed of implementation and cost efficiency and is compatible with national and EU policies.

Call to action | National governing bodies must decide on ownership allocation of hub foundations.

An all-electric platform-based hub could be most naturally owned and developed by an electricity TSO, whereas inclusion of gas transmission infrastructure could call for shared ownership between electricity and gas TSOs. However, this is not possible within existing regulatory frameworks. When considering multi-functional or island-based solutions for the hub, a dominant role for the various governments is expected. More specifically, a public-private partnership (as chosen for the Danish energy islands) may be considered for island-based solutions. Benefits of this arrangement include price and quality competition in the tendering phase as well as the encouragement of innovative activities by the project company.

Call to action | National governing bodies must decide on a regulatory regime for interconnectors between national hubs.

National regulatory authorities need to decide on cost and benefit allocation between the respective TSOs developing and operating the interconnection assets. More specifically, a commercial model for the possible interconnections needs to be considered, requiring more detailed discussions on commercial arrangements.

Given the novelty of hub-and-spoke project concepts, a suitable governance model has yet to be defined. The consortium presents a governance model concept for first hub-and-spoke projects. The described governance model will be further investigated regarding its implications for specific case studies (configurations, capacities, and layout of envisioned hub-and-spoke projects).

Key message 4

Financing and cost recovery of hub-and-spoke projects can be largely covered by existing financial and economic frameworks.

Concept | The economic and financial framework refers to all financial streams, cost recovery, and financing mechanisms. We consider three building blocks of a project: planning, ownership, and system operation, and take the above discussed governance model as starting point.

Financing and cost recovery of the hub-and-spoke project for electricity appears to be possible within the current frameworks at a national level. Arranging the financing and cost recovery of a hub-and-spoke project within the existing frameworks, might ease the implementation and development of these projects. This is due to the hub-and-spoke configuration where only the hub-to-hub interconnectors are international and cross-border whereas all other assets can be seen as national assets.

Especially the Danish frameworks are considered already very suitable for hub-and-spoke projects considering that they have a political agreement for a framework for hub foundations. Furthermore, the Danish framework for electricity transmission and interconnection was developed for a broad range of assets, making it a relatively simple fit for the hybrid projects.

In Germany, a combination of the existing frameworks can cover most of the electrical elements of a hub-and-spoke project. There are a few aspects that need further consideration, these include:

- It remains uncertain by which framework hub-to-hub or hub-to-shore *interconnectors* can be covered, given that interconnectors between onshore points are regulated as onshore assets.

- Depending on the type of hub and the activities that will be conducted on the hub and whether these fit in the legal tasks of either the gas or electricity TSO, the *hub foundation* can be covered by the existing offshore framework, or in case of a multi-purpose hub, a new framework should be timely developed.

- Finally, German frameworks do not allow *anticipatory investments*, while these are especially relevant for hub-and-spoke projects due to its modular character character (see section on modularity in Technical feasibility).

For the Netherlands, it is found that using a combination of frameworks is most suitable to ensure financing and cost recovery of the assets in a hub-and-spoke project. The offshore framework can cover the offshore converter station, offshore transmission line, offshore hub foundation (if the hub does not host other activities than directly related to the legal task of the TSO), hub electrical transmission assets, and activity system planning. There are a few aspects which require more attention. The *legal offshore grid definition* states that the offshore grid can only be used to transport energy from the directly connected offshore wind farms to the onshore transmission grid (and therefore not for interconnection flows). Therefore, legal changes are required in case an interconnector will be connected to the offshore grid. Like Germany, depending on the type of *hub* *foundation* and the activities that will be conducted on the hub, the hub foundation can be covered by the existing offshore framework. In case of a multi-purpose hub, a new framework should be developed which allows the responsible parties to recover the planning, ownership, and operation costs.

Financing and cost recovery of the hub-and-spoke project may be possible at a national level but leveraging European funding schemes may help reduce the burden on the tariff and taxpayers. Analysis shows that in all countries a European fund can be part of the national economic and financial frameworks. It is, perhaps, surprising that the funds do not have a very large positive impact for the TSO[3]. However, they can benefit the public acceptance of large infrastructure projects and the reputation of the developer. Applying for grants is very time and resource intensive and may not be attractive from a business perspective and may slow down the development of such an innovative project. At the same time, the development of hydrogen assets requires subsidies to make the hydrogen value chain competitive with carbon-based fuels.

Finally, the use of congestion income is discussed considering an EC proposal to be published in 2022 on the alternative uses of congestion income. The European Commission is considering opening the European regulation on usage of congestion income to mitigate the negative impact of an offshore bidding zone on offshore wind farm investment certainty. Differing regulation between the countries causes differences in how congestion income is spent. The implications of the EC proposals are far reaching and are discussed in detail:

- Impact of advanced hybrid coupling on the correlation between congestion income and OWF revenues

- Furthermore, opening up congestion income regulation can have a negative impact on the compliance with European regulation which stipulates that network charges shall be cost reflective and shall not include unrelated costs supporting unrelated policy objectives

- The resulting mix up of levies and tariffs when opening congestion income regulation. Especially, the interference of member states in NRA power should be further considered

- Other mechanisms might be more suitable to ensure sufficient OWF income than the redistribution of congestion income approach. More research is required to examine this.

Call to action | We recommend the national governments to provide clarity on hub-and-spoke aspects that cannot yet be covered within financial and economic frameworks. This clarity must be provided before the final investment decision can be made.

This includes amending the framework for interconnectors to accommodate hub-to-hub and hub-to-shore interconnectors, developing a framework for multi-purpose hub foundations, if necessary, as well as allowing a certain level of anticipatory investments.

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[3] Applications for European grants come with a lot of terms and conditions. It may even be the case that applying for European subsidies results in more work and less income since these application hours and efforts won't get reimbursed. Furthermore, not receiving subsidies for specific (innovation) projects can hinder and delay project developments.

Conclusion

Our changing energy landscape calls for immediate actions and innovative solutions. Countries have turned their eyes to the North Sea as the new green power plant for Europe. The ambition of Denmark, the Netherlands, Germany, and Belgium is to develop 65 GW of offshore wind by 2030 and 150 GW 2050. The importance of cross-border cooperation and interconnection is stressed in the multilateral and bilateral agreements. The NSWPH Project of Common Interest has moved from an ambitious novel concept to receiving concrete political buy-in. We are proud to have contributed to these developments and look forward to further supporting national governments in knowledge development and decision making.

In the feasibility phase of the NSWPH project, we have booked major progress in our four core activities: system integration, technical feasibility, costs and benefits, and regulatory and market design. We showed that an interconnected North Sea grid is beneficial for system integration in 2050. In addition, we demonstrated the feasibility of individual elements of the hub-and-spoke concept, including offshore power-to-gas, hydrogen infrastructure, caisson-based islands, and HVDC infrastructure. We successfully applied our cost benefit analysis methodology to hub-and-spoke case studies across sectors, countries, and energy carriers. We identified key drivers for a positive CBA and show that the hub-and-spoke concept is a future-proof way for offshore infrastructure build-out.. On the regulatory and market aspects, we demonstrated how offshore bidding zones, governance models, and economic and financial frameworks can be implemented.

We are excited for the future of the North Sea and look forward to continuing the further development of the concept. While we have booked major progress in our understanding of the hub-and-spoke concept, there’s still plenty to uncover. We will focus our efforts on finetuning our energy system studies and cost benefit analyses to fully understand the drivers for beneficial project configurations and to properly capture the benefits. In addition, we continue to fill in the knowledge gaps in terms of technical, and regulatory and market aspects. We are dedicated to continuing to share our knowledge with national governments to support national developments.

Next Steps

1

Energy system studies
We will make continuous improvements to our energy systems modelling. The goal is to build a model that can assess how a balanced future system between electricity and hydrogen could develop given certain demand scenarios. We plan to execute a follow-up to the Pathways study in 2023 with updated energy system scenarios and further refined methodologies.

2

Cost benefit analyses
We will refine the CBA methodology and execute sensitivity analyses on overplanting of offshore wind, price of hydrogen imports, electricity- and hydrogen grid buildout options, and fossil fuel & CO_2 prices. Continuation of timely communication with- and consultation of stakeholders is part of the upcoming process and important for ensuring results of quality.

3

Technical concept development
We will continue to deepen our technical understanding of hub-and-spoke elements to further develop the concept over the next year. This includes:

- Power-to-gas concept designs for caisson islands as well as grid-integrated hydrogen offshore wind turbines, and electrical integration aspects of electrolysis.

- Operational philosophies that consider the effect of hydrogen production profiles, pressure levels, pressure fluctuations and temperature on the compatibility of the pipeline material with hydrogen

4

Regulatory & market design
We will further develop our understanding of energy system balancing in an offshore bidding zone set-up and assess suitable governance and financial-economic frameworks for unique hub-and-spoke elements. We continue to support national governments in their decision making on regulatory and market aspects of offshore infrastructure development.

5

Stakeholder engagement and communication
We are dedicated to contributing to national offshore wind and infrastructure roll-out developments. We will therefore continue to engage with national governments and other stakeholders along the value chain to share our vision and knowledge of a cost-efficient system integration of offshore wind. In addition, the hub-and-spoke concept is not limited to the North Sea. We will therefore continue to share our knowledge through publication of concept and discussion papers.

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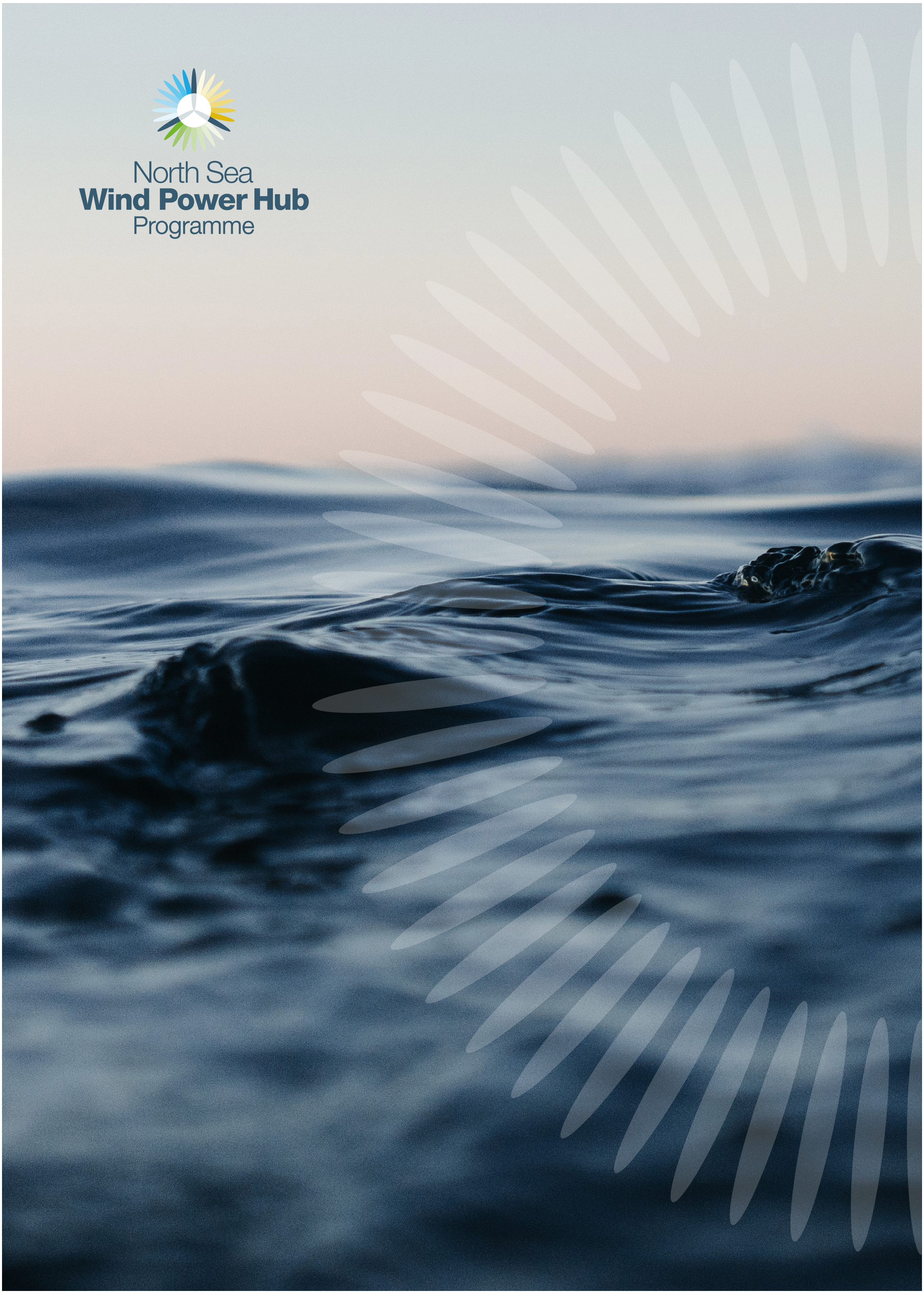

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