North Sea
Wind Power Hub
Programme

Towards the first hub-and-spoke project

Progress of the North Sea Wind Power Hub Consortium

Concept paper
2021

Co-financed by the Connecting Europe Facility of the European Union

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

Executive summary

The North Sea is an offshore wind energy powerhouse

The North Sea holds a vast offshore wind energy potential. Offshore wind is one of the key building blocks for the green transition of Europe and to meet the Paris Climate Goals. This is reflected by the 2050 capacity target of 300 GW set by the European Commission.

Countries must come together

So far, energy policies in Europe have been mostly nationally focussed with international cooperation only recently starting up. Further acceleration of cooperation initiatives is required to realise the full potential of the North Sea: The increasingly large and variable volume of offshore wind electricity will be difficult to integrate, and there is no single silver bullet solution.

Why this concept paper?

In this concept paper we share our latest and most important insights developed during the pre-feasibility phase of the North Sea Wind Power Hub programme. In this phase, which ran from June 2019 to February 2021, we moved from a broad assessment of the possible role of a hub-and-spoke concept to a clear understanding of what is needed to realise a first hub in the early 2030s.

In June 2019, we issued a first series of concept papers capturing our latest insights at the time. The programme has since entered a new phase and developed much more specific insights on how an internationally coordinated approach can facilitate the roll-out of offshore wind and the energy transition as a whole.

The previous concept papers are accessible at the following webpage www.northseawindpowerhub.eu/concept-papers-challenge-solution-and-next-steps/.

Time for an ambitious next step

Harnessing the power of the North Sea requires us to look at the whole North Sea area as one, and comprehensively rethink the energy systems of all of North-West Europe. This large-scale thinking is the only way to timely meet decarbonisation targets.

A solution is at hand

The North Sea Wind Power Hub (NSWPH) is an ambitious new approach to the challenge of integrating renewable energy. Today, climate policy is largely national, decoupled between energy sectors and incremental. The NSWPH takes a very different perspective. It is transnational, integrated and a step-change to a massive build out of offshore wind in the North Sea. The hub-and-spoke concept is able to link together the energy systems of North-West Europe in one well-planned and coordinated network while connecting large amounts of offshore wind. It has unique characteristics:

- Transnational: by connecting multiple countries through a hub-and-spoke concept
- Hybrid: by combining interconnection with the connection of offshore wind
- Cross-sector: by integrating different energy sectors and energy carriers

Cooperation is the way forward – The NSWPH consortium is helping to pave the way

The NSWPH consortium was founded in March 2017 and consists of the leading TSOs of North Sea Countries; Energinet, Gasunie and TenneT. Our work focusses on timely addressing the main challenges on the way to realising a first hub in the early 2030s, and to support governments and policy makers in their decision-making processes.

Main insights

Given the long lead times of large-scale offshore infrastructure projects, several challenges need to be solved early on to provide investment certainty to project developers and stakeholders. We continuously conduct analyses to support decision-making 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 overarching topics that we developed over the previous 1.5 years during the pre-feasibility phase of the first hub-and-spoke project:

System Integration

How can a hub-and-spoke concept help to reduce mismatches between supply and demand, improve security of supply and support decarbonising non-power demand sectors?

Our main insight | The hub-and-spoke concept provides a solution through the integrated system approach: by increasing the connection between countries, and by converting electricity to other forms of energy that can be stored more cheaply and can be used in non-power demand sectors.

Technical Feasibility

What is the range of feasible hub-and-spoke configurations and how do they compare?

Our main insight | We evaluated different configurations for the first hub project, against feasibility and economic drivers. We understand the critical issues and pros and cons of different configurations and we are ready to support governments to prepare for decision-making towards a first hub-and-spoke project.

Cost & Benefits

How can we develop a new internationally accepted perspective for a suitable cost and benefit analysis (CBA) framework for hub-and-spoke projects?

Our main insight | We developed guiding principles to change the perspective on current CBA approaches to kick-start a stakeholder dialogue.

Regulation & Market design

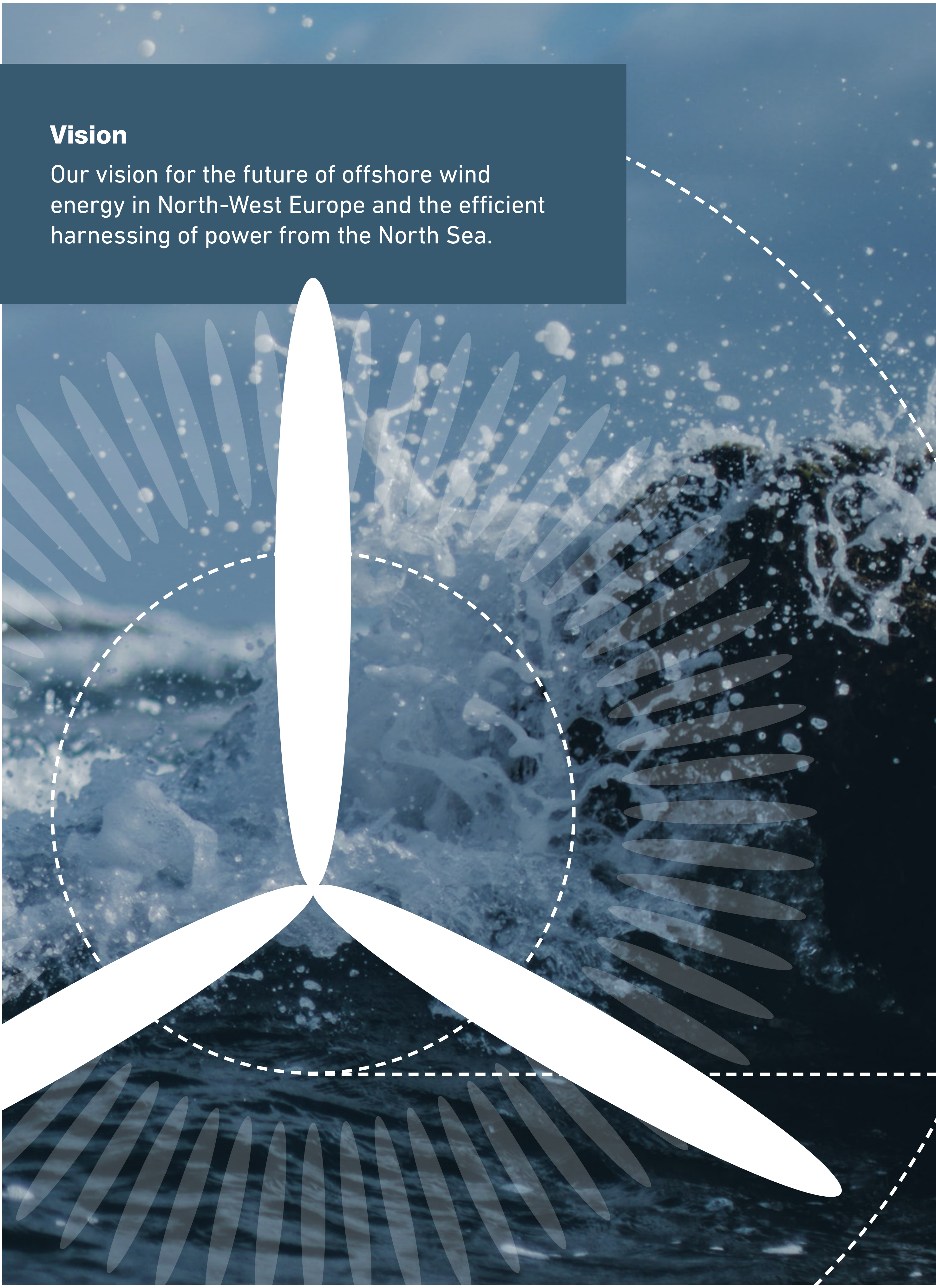
How can we ensure that governments make the necessary decisions at the right time?

Our main insight | We have identified an integrated decision-making timeline to realise the first hub project in the early 2030s that considers interdependencies across key regulatory and policy topics.

The NSWPH consortium reaches out and calls upon all stakeholders who want to work towards a solution, to step up and contribute. No single actor can bring about the change we need. It requires teamwork and a broadly shared commitment.

Vision

Our vision for the future of offshore wind energy in North-West Europe and the efficient harnessing of power from the North Sea.



A solution for achieving the 2050 emissions goals

The hub-and-spoke concept offers a solution to the challenge of integrating renewable energy – we intend to facilitate the realisation of a first project in the early 2030s.

The North Sea is an offshore wind energy powerhouse

Over the coming ten years, the roll-out of renewable energy needs to accelerate. By 2030, greenhouse gas emissions in the EU need to decrease by 55% compared to 1990 levels. Concurrently, the use of primary energies (fuels, gasses) should decarbonise as well. Achieving net-zero emissions by 2050 is essential and part of EU policy. Offshore wind is one of the main sources of renewable energy to realise this, reflected by the 2050 capacity target of 300 GW set by the European Commission (EC). The North Sea will play a key role in achieving these targets; exploiting the offshore wind potential in the North Sea could not only provide a large share of the electricity consumption of the countries bordering the North Sea but also produce electricity to make hydrogen, fuels and produce heat. Offshore wind in the North Sea could produce significantly more electricity than the average demand of the bordering countries. This massive potential must be harnessed if we are to meet the Paris Climate Goals.

Countries must come together

So far, energy policies in Europe have been mostly nationally focussed with international cooperation only starting to progress. Further acceleration of cooperation initiatives is required to realise the full potential of the North Sea, as we need a comprehensive and integrated solution that is transnational. The increasingly large and variable volume of offshore wind electricity will be difficult to integrate, and there is no single silver bullet solution. While exploiting the full potential of offshore wind in the North Sea will require large investments, the main reason for international cooperation is that the massive amount of wind power we can generate is unevenly distributed between countries and requires regional balancing. We need all countries working together.

One insight that has blown our minds

Offshore wind in the North Sea could produce significantly more electricity than the average demand of the bordering countries.

Time for an ambitious next step

Harnessing the power of the North Sea requires taking an ambitious next step in the green energy transition. An energy system driven by renewables that provides security of supply and maximum societal benefits requires a holistic and transnational energy system planning approach. This means consideration of production, demand, transmission/transport, electricity conversion and storage of electricity and electrofuels (also referred to as e-fuels and synthetic fuels)[1]. System integration enables the design of an energy system that accounts for these elements and enables formulating the trade-offs beyond a single sector, energy carrier and country border. Only through transnational and cross-sector collaboration will we be able to realise a timely and cost-effective transition. This requires us to look at the whole North Sea area as one, and comprehensively rethink the energy systems of all of North-West Europe. This large-scale thinking is the only way to timely meet decarbonisation targets.

A solution is at hand

The North Sea Wind Power Hub (NSWPH) is an ambitious new approach to accelerating the green transition and to meeting the Paris Climate Goals: The hub-and-spoke concept offers a solution to the challenge of integrating renewable energy and ensures a cost-effective and step-by-step deployment by combining assets and functions. The hub-and-spoke concept combines electricity transmission from wind farms to shore with interconnectors (hybrid), and facilitates the integration of gas, electricity and heating sectors through Power-to-X conversion. Zero CO_2-emitting dispatchable power generation is needed as well, and the Gas-to-Power route provides this option.

Today, climate policy is national, decoupled between energy systems and sectors and incremental. The NSWPH takes a very different perspective. It is transnational, integrated and a step-change to a massive build out of offshore wind in the North Sea. The hub-and-spoke concept is able to link together the energy systems of North-West Europe in one well-planned and coordinated network while connecting large amounts of offshore wind.

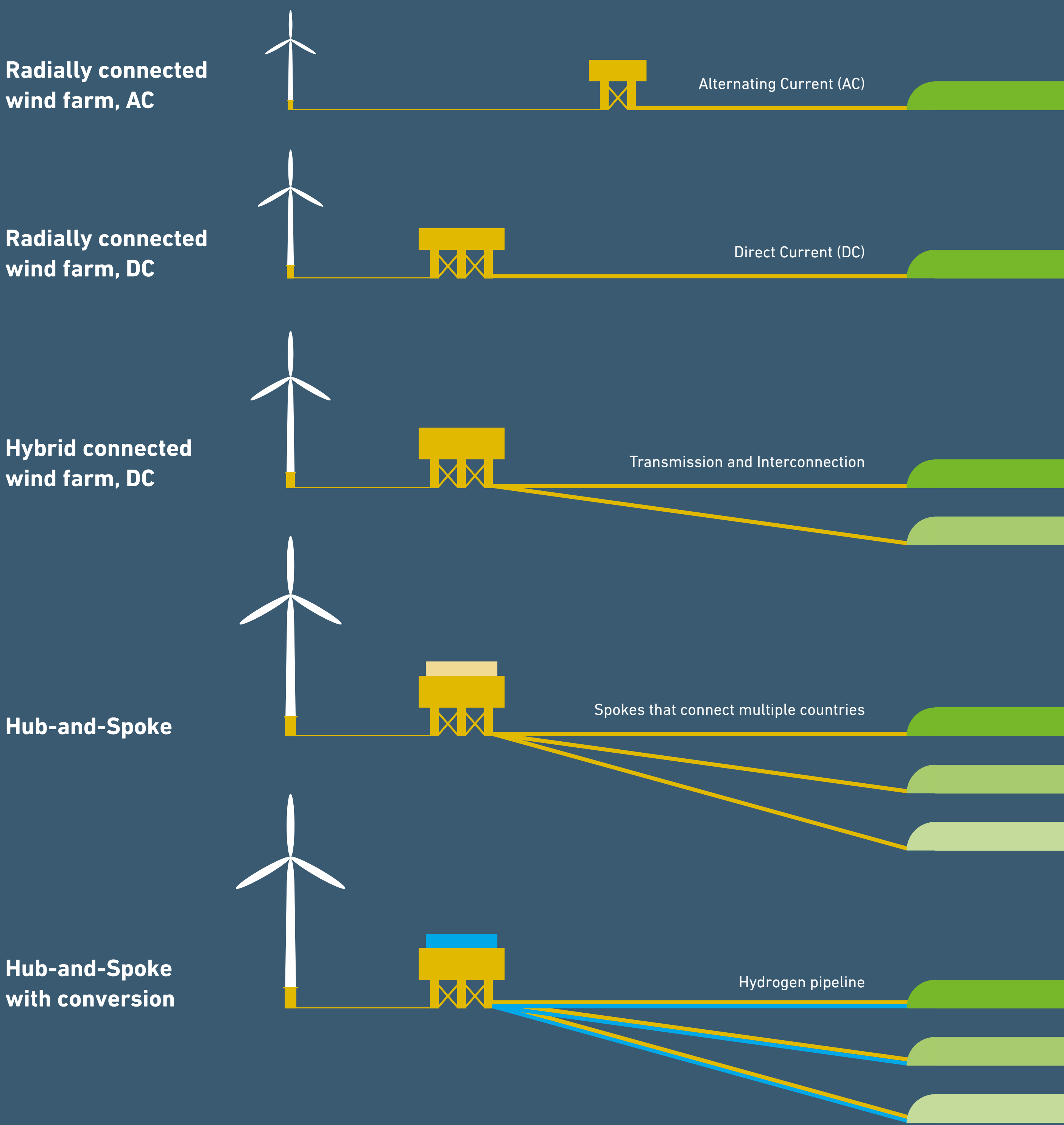
As a group of leading Transmission System Operators (TSOs) for gas and electricity grids, we set out to make this project a reality. Our work focusses on timely addressing the main challenges before a first hub can be realised in the early 2030s, to support governments and policy makers in their decision-making processes. To do this, we continuously conduct analyses to support decision-making and investigate the broader energy system impact of the concept, the costs and benefits, the regulatory changes required and a fitting market setup.

We are committed to develop the offshore energy infrastructure for the future, acting out of our social responsibility to enable the energy transition and reaching the climate goals in time.

[1] Electrofuels are produced by storing the energy from (renewable) electricity in chemical bonds. The category includes gaseous fuels (such as hydrogen, methane) and liquid fuels (such as synthetic kerosene, butanol, and e-diesel). The production process usually starts with the electrolysis of water into hydrogen and oxygen, and can include CO_2 as a feedstock to produce carbon-based electrofuels.

Hub-and-spoke is a next step in the evolution of offshore wind connections

The evolution is ongoing: From near-shore radial alternating current (AC) connections to far offshore direct current (DC) connections. The hub-and-spoke concept is another step in this evolution, adding interconnection and potentially electricity conversion.



Situation

Over the last year, significant steps have been taken to accelerate offshore wind deployment and international cooperation efforts for developments towards the post-2030 horizon. However, international cooperation needs to continue and accelerate.

Post-2030 energy strategies enable decisions and planning towards 2050

North Sea Member States have typically defined offshore wind targets and planning up to the 2030 horizon, leaving uncertainty around post-2030 developments. Post-2030 strategies and targets on a Member State level are required to accelerate offshore wind deployment rates and integration into the wider energy system towards 2050. Plans on a country-level are required to set specific targets for offshore wind, system integration, infrastructure and other energy carriers. Development milestones need to be defined and regulatory, spatial and infrastructure planning for the 2030 to 2050 period is needed. A stable market outlook in this timeframe builds industry confidence and supports supply chain development. The coming years will be critical due to the long lead times for decisions, agreements and developments on technology, configurations and regulation.

International cooperation between North Sea countries on offshore hybrid projects is developing but needs to accelerate to move towards project development

Offshore hybrid projects are building blocks for an international offshore energy system. In 2020, there was increased attention for international cooperation and the business case of hybrid projects.

The hub-and-spoke concept has become more concrete

Since our previous concept papers, published in 2019, we further progressed the hub-and-spoke concept and we will now enter the feasibility stage. We have successfully promoted the TYNDP project 'Project #335 North Sea Wind Power Hub', which has been awarded the Project of Common Interest (PCI) status by the European Commission in 2019 and we have secured funding provided by Connecting Europe Facility (CEF), recognising it as one of the missing links in Europe's energy backbone. The programme has secured several years of future work and has clear milestones, deliverables and obligations.

Key concept | Hybrid project

Traditionally, separate electrical connections were used to connect wind farms to shore on the one hand (wind farm transmission), and to connect countries to each other on the other hand (interconnection). In a hybrid project, there are electrical connections from the wind farm to multiple countries. This combines the two functions and the connections are used more efficiently. Together with international cooperation, hybrid projects play a key role in integrating the planned large-scale deployment of offshore wind in Europe.

Accelerated developments in 2020

Offshore wind and international collaboration

In November 2020, the European Commission (EC) published the EU Offshore Renewable Energy Strategy[i] aiming for the development of 300 GW of offshore wind complemented by 40 GW of other offshore energy technologies by 2050. This is a significant step in materialising post-2030 developments in the EU sea basins.

Denmark announced its target of developing two energy islands[ii]: Bornholm in the Baltic sea (2 GW) in the early 2030s and an artificial island in the North Sea (3 GW by 2030 or as soon as possible thereafter, then later extended to up to 10 GW), emphasising the role of international connections. As next steps, the Danish Government will determine the specifics of the joint public-private ownership model for the North Sea island and carry out environmental impact assessments.

In December 2020, the Netherlands published the North Sea Energy Outlook[iii], for the first time stating ambitions for offshore wind capacity by 2050: between 38 and 72 GW. This Outlook will form the basis for further target setting and offshore planning activities in the coming year.

Germany adopted increased targets for offshore wind in 2020: 20 GW by 2030 and 40 GW by 2040.[iv]

Several EU countries started formal collaboration related to the offshore hub-and-spoke concept: In December 2020, The Netherlands and Denmark signed a Memorandum of Understanding on cooperation on offshore energy infrastructure.[v] In 2020, the Netherlands and Germany signed a Joint Declaration on further co-operation regarding grids and electricity transmission[vi], and Denmark and Germany signed a Letter of Intent on Jointly Analysing Joint and Hybrid Offshore Renewable Energy Projects between the Countries[vii].

Hydrogen and system integration strategies

In parallel to offshore wind development targets, sector coupling and hydrogen strategies are being rolled out. The EC published its hydrogen strategy, aiming to develop at least 40 GW of electrolysers by 2030.[viii] In addition, the EC also published its energy system integration strategy. On a Member State level, national hydrogen strategies in the Netherlands and Germany show ambitions for system integration.

The Dutch Ministry of Economic Affairs and Climate Policy has investigated the benefits of a combined tendering process, which includes offshore wind and green hydrogen production, and is starting a study to investigate the optimal way to transport offshore wind energy (electricity and hydrogen) to shore.[ix]

At an EU level, the EC offshore renewable energy strategy identified a key role for hybrid projects to scale up offshore wind deployment from 2030 onwards.

Offshore hybrid projects and hydrogen are also key focus areas of the proposed 2021 revision of the European TEN-E regulation.[x]

Insights

Our work focusses on addressing the main challenges on the way to realising a first hub. Given the long lead times of large-scale offshore infrastructure projects, several of these challenges need to be solved early on to provide investment certainty to project developers and stakeholders. In this paper, we share our insights on four overarching topics that we developed over the previous 1.5 years during the pre-feasibility phase of the first hub-and-spoke project.

System Integration

Situation | The share of variable renewables in the electricity mix in Europe is growing, in some countries this is leading to increasing periods of low electricity spot prices and curtailment.

Challenge | Transforming today's electricity generation mix to one with predominantly variable renewable generation limits the ability for generation to follow demand, leading to mismatches between generation and demand. Decarbonising non-power demand sectors further, massively increases the need for renewables and requires conversion of electricity to other energy carriers.

Question | How can a hub-and-spoke concept reduce mismatches between supply and demand, improve security of supply and support decarbonising non-power sectors?

Our main insight | The hub-and-spoke concept provides a solution through the integrated system approach, by increasing the connection between countries and by converting electricity to other forms of energy that can be stored more cheaply or used in non-power demand sectors.

Costs and benefits

Situation | A positive societal Cost-Benefit Assessment (CBA) outcome is a prerequisite to realise energy infrastructure projects: societal benefits must outweigh the societal cost of the investment.

Challenge | Transnational, hybrid and cross-sector projects have unique characteristics that require a new approach to CBA, as they have a much deeper impact on energy infrastructure. Existing single-sector CBA approaches are not adequate.

Question | How can we develop a new internationally accepted perspective on a suitable CBA framework?

Our main insight | We developed guiding principles to change the perspective on current CBA approaches to kick-start a stakeholder dialogue.

Technical feasibility

Situation | Hub-and-spoke projects combine several existing and a few novel technologies through a large number of potential technical project configurations.

Challenge | Development of the first hub requires decisions on the configuration of the project. This requires addressing critical issues in the development and available technologies based on an integrated energy system perspective, to ensure efficient integration of large-scale variable renewable energies, including sector-coupling, storage and efficient transport of energy.

Question | What is the range of feasible hub-and-spoke configurations and how do they compare?

Our main insight | We evaluated different configurations for the first hub project and the required technical elements. We understand the critical issues and pros and cons of different configurations, and are ready to support governments to prepare for decision-making towards a first hub-and-spoke project.

Regulation & Market design

Situation | Current national and EU-level policies and regulatory frameworks are not suited to govern hub-and-spoke projects.

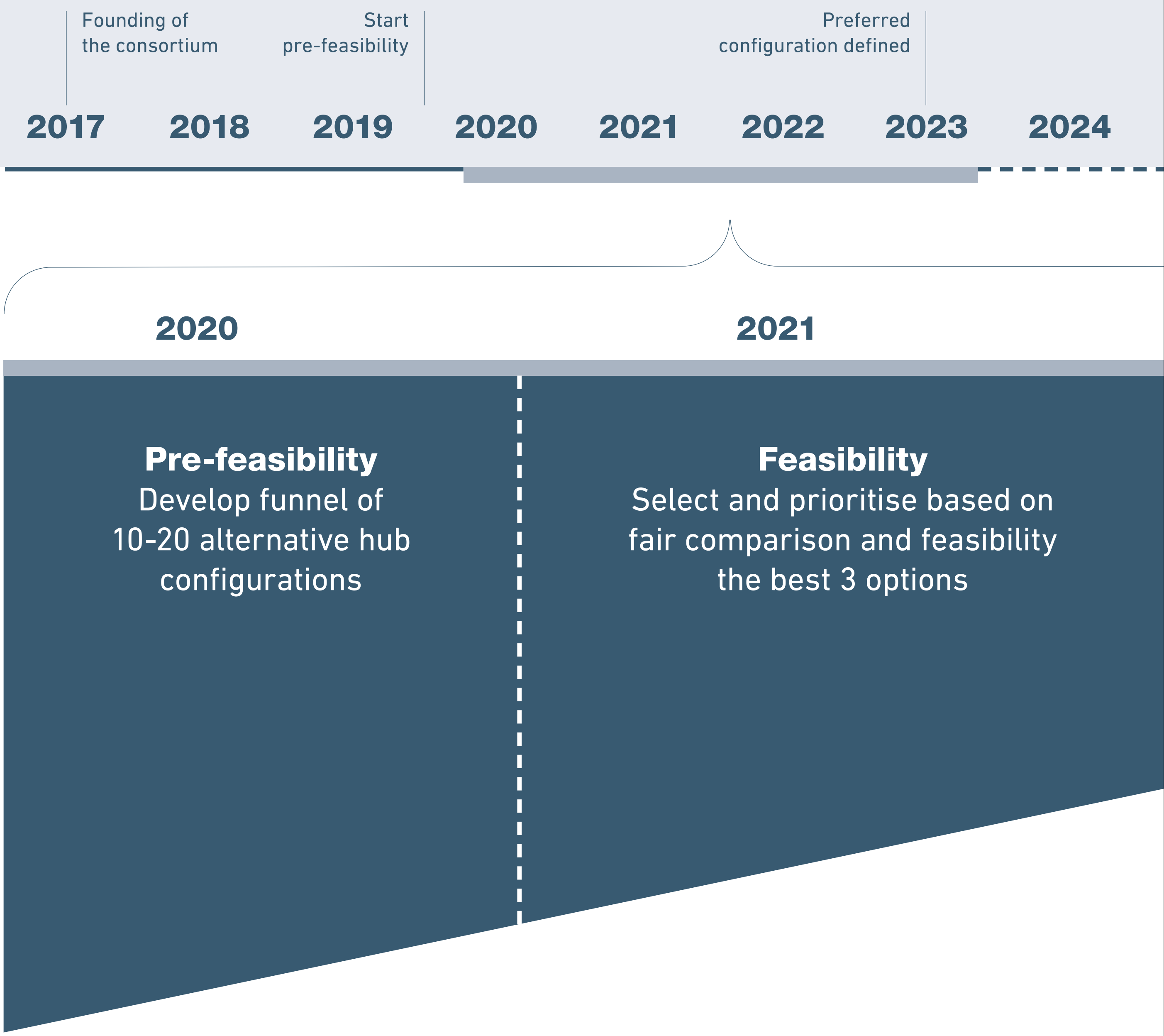
Challenge | Timely policy decisions and international cooperation are critical for project success. Clarity on policy and regulation is required to provide investment certainty and to reduce risks.

Question | How can we ensure that governments make the necessary decisions at the right time?

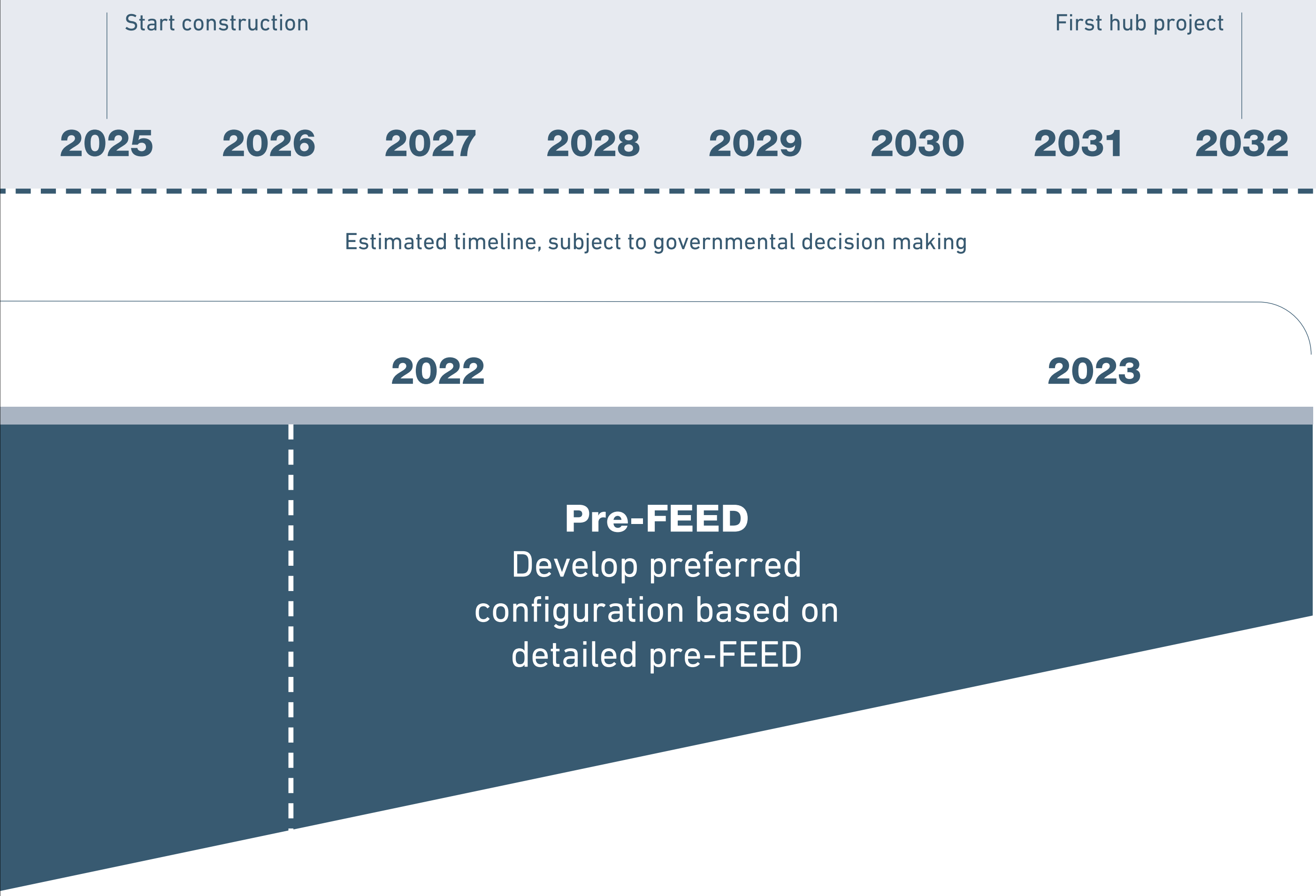
Our main insight | We have identified an integrated decision-making timeline to realise the first hub in the early 2030s that considers interdependencies across key regulatory and policy topics.

Approach of the Consortium

Structured and transparent international cooperation is key to taking this next step in offshore developments. The North Sea Wind Power Hub consortium reaches out and calls upon all stakeholders who want to work towards a solution, to step up and contribute. No single actor can bring about the change we need on its own. It requires teamwork and a broadly shared commitment. Reaching the goals of the project also requires the role of TSOs to move beyond national borders. We stand ready to support governments and societies with our deep expertise to enable timely decision-making and realise a first hub project in the early 2030s.



We take a structured funnelling approach, that supports relevant governments to take decisions on the scope and location of a first hub-and-spoke project in 2023. This funnelling process is organised in three phases: pre-feasibility, feasibility and pre-FEED (pre- Front-End Engineering and Design). With each step, the range of considered project configurations decreases and the level of detail in our studies increases. We intend to carry out the funnelling of configurations in close collaboration with the relevant ministries. We have completed the pre-feasibility phase and are now entering the feasibility phase.



System Integration

How to adapt the energy systems in North-West Europe to integrate a large volume of offshore wind from the North Sea.

The future energy system of North-West Europe will be deeply integrated

System integration enables balancing energy supply and demand in time, and supports decarbonisation of non-power sectors.

What we have learned

- The future decarbonised power system requires large amounts of flexibility.
- Hydrogen can play a vital role in cost effectively integrating large volumes of offshore wind energy.
- It is currently cost effective from a total energy system perspective to integrate electricity and hydrogen production since this setup facilitates a further reduction of fossil fuel based power generation besides the production of hydrogen.
- Domestic green hydrogen production plays a role in cost effective system integration, even when cheap imports are available.
- Further integration of the electricity, gas and other energy sectors is a necessity and lowers total system costs.

What do we need to study/learn next

- Conduct multiple in-depth studies to gain further specific insights into system integration, including on energy landing zones, energy conversion and supply chains, innovation and technological readiness.
- Continue to develop evidence-based discussion papers tackling the above techno-economic study results.

One insight that has blown our minds

Even when cheap hydrogen imports are available in the future, an optimised system includes substantial domestic hydrogen production.

How can a hub-and-spoke concept help to reduce mismatches between supply and demand, improve security of supply and support decarbonising non-power sectors?

The hub-and-spoke concept provides a solution through the integrated system approach: by increasing the connections between countries and by converting electricity to other forms of energy that can be stored more cheaply or used in non-power demand sectors.

System integration aims to adapt the energy systems in North-West Europe to integrate a large volume of offshore wind from the North Sea. We work to find ways to balance energy supply and demand in time. This will ensure we have use for wind energy even at peak generation, as it supports decarbonisation of the non-power sectors like transport and heavy industry. In case of low wind, system integration will ensure that sufficient zero-emission dispatchable power is available.

System integration offers a solution to the mismatch between supply and demand by coupling different energy carriers, infrastructures and end-use sectors

Transforming today's electricity generation mix to one with predominantly variable renewable generation limits the ability for generation to follow demand, resulting in mismatches between generation and demand. New types of flexibility in generation and demand are required, where zero-carbon dispatchable power will play an important role. Renewable electricity will also drive decarbonisation of non-power demand sectors (such as industry, shipping and aviation), for which energy conversion is necessary.

Our vision is that system integration offers a solution to these challenges. System integration is the coordinated planning and operation of the energy system across multiple energy carriers, infrastructures, and end-use sectors. This includes physically linking different energy carriers (electricity, heat, fuels) with each other and with different end-use sectors (industry, transport, buildings).

The concept of system integration focusses on the following pillars:

1. The roll-out of offshore wind should be undertaken in parallel with the creation of additional electricity demand. Decarbonisation of energy demand can be done via direct or indirect electrification (zero-carbon fuels, gas and liquid). The most effective solution varies from sector to sector and even from case to case.
2. System integration should be undertaken across national borders.
3. Flexibility is needed to maintain secure and balanced energy supply. All forms of flexibility need to be considered: dispatchable generation, interconnection, storage, conversion and demand side management.

Our focus is to define solutions that will enable meeting future energy needs in a way that maximises societal benefits.

Key concept I Flexibility

The demand for electricity is continuously changing: from minute to minute, from day to night, from summer to winter. We need a way to provide enough electricity to meet this demand at all times. If we fail to do that, power cuts can be a result. So far, we mostly control gas-fired plants to generate more or less electricity to follow the demand. This is called flexibility. In the future energy system, we will have much less gas-fired plants and much more renewable power that follows weather patterns requiring new sources of flexibility.

Situation

Emissions reduction: Big steps have been taken, giant leaps are still needed

Key concept I Power-to-X

Power-to-X means converting electricity to another energy carrier. In our definition this includes hydrogen, synthetic fuels (liquid and gaseous) and chemicals. These renewable products enable us to decarbonise energy users that currently need fossil fuels, including chemical companies.

2020 was a milestone year regarding decarbonisation of the EU electricity markets: renewables (38%) overtook fossil fuels (37%) in the annual electricity mix.[xi] Denmark (62%), Ireland (35%) and Germany (33%) are leaders in solar and wind energy shares, while the Netherlands (19%) saw an impressive 40% increase compared to 2019, bringing its share in line with the EU average (20%)[xi]. In order to reach the EU's new 55% emissions reduction target for 2030, annual wind and solar energy growth must double compared to 2020 levels (from ~50 TWh/yr to ~100 TWh/yr[xi]). Current national renewable energy roll-out plans fall short.[xi]

By 2050, all energy sectors must be decarbonised. In Europe, electricity currently only makes up about 25% of final energy demand. The EC envisages this share could more than double due to electrification, but a demand for fuels (gas and liquid) will remain.[xii] Renewable electricity can be converted and used to produce electrofuels to decarbonise (part of) this demand. In a nutshell, we need a lot more renewable energy: about 2.5 times the current volume to decarbonise the current electricity demand, and 5 times the current volume to decarbonise the future electricity demand.

Energy sectors have largely developed in parallel. Coordination is commencing and the NSWPH consortium is working to accelerate the integration of the gas and electricity sectors

Historically, the gas and electricity energy sectors have been developing in parallel. In Germany and the Netherlands, for example, different Transmission System Operators (TSOs) develop gas and electricity infrastructure. This is not the case in Denmark, where Energinet is TSO for both gas and electricity networks. The gas and electricity TSOs collaborate in separate European associations, e.g. ENTSOG (gas) and ENTSO-E (electricity). ENTSO-E and ENTSOG historically developed their ten-year network development plans (TYNDP) separately. Coordination of developments in these two sectors is increasing, for example, ENTSOG and ENTSO-E are working towards developing a joint TYNDP scenario set, and the Dutch TSOs have published a joint infrastructure outlook.

In the NSWPH consortium, we are working together not only to integrate infrastructure planning, but to integrate these sectors as a whole. This includes the integration of generation and demand, as well as infrastructure.

The biggest integration challenge is the mismatch between energy supply and demand over time

Cost reduction and stimulating policies enable rapid growth of renewables. As a result, large capacities of renewables need to be integrated efficiently into the energy system. Two types of integration challenges need to be overcome:

1. The spatial integration challenge: grid constraints that limit the transport of energy, which can be exacerbated as net inland power generation reduces and offshore generation increases.
2. The temporal integration challenge: the mismatch between generation and demand over different timescales.

In the European climate, in particular, the challenge of temporal integration at timescales of weeks to seasons is becoming increasingly important with higher levels of renewables in the system: in winter, solar photovoltaics (PV) delivers little electricity while wind energy may show large variations over periods of weeks.

We urgently need policies that stimulate demand for renewable energy in its different forms (electricity, electrofuels, hydrogen, heat). Without those, the roll-out of renewable generation and demand creation will not happen in sync, resulting in curtailment, imbalances, and a deterioration of the business case for renewables. In addition, we need policies that stimulate the reduction of energy consumption during times of limited renewable energy production.

Cost reduction in renewables and developments in electrolysis are enablers for system integration

The cost of offshore wind has dropped significantly over the last decade. Subsidy tariffs in Germany and the Netherlands in 2009-2011 were in the order of 150-185 €/MWh, while in 2017-2020 competitive tender processes in both countries resulted in several winning zero-subsidy bids.[2] This indicates a current cost level in the range of 40-50 €/MWh. In 2019, the UK Round 3 offshore wind tender saw a similar average result of around 40 £/MWh[xiii] (~47 €/MWh).

Electrolyser developments are accelerating in parallel. Commercial application of the technology has been around since 1927[xiv], but thus far production processes were focussed on the chlorine industry. Electrolysis of water, as required for hydrogen production, still concerns small-scale, labour intensive installations. While the investment cost for new smaller scale installations (10-20 MW) are in the order of 1,000 €/kW, rapid cost reduction is expected for larger scale installations. IRENA assessed the potential cost decrease of electrolysis based on learning rates and assumed levels of deployment, arriving at 300-400 €/kW in 2030 and 120-200 €/kW in 2050[xv].

While the level and pace of cost reductions are uncertain, there are promising signs. Industrialisation is taking place, and in January 2021 ITM Power completed its first GW-scale factory[xvi]. Similar plans and initiatives for GW-scale facilities have been announced by Thyssenkrupp[xvii] and NEL Hydrogen[xviii]. Continuing industrialisation, increasing scale, and learning-by-doing will enable cost reduction and as a result enable green hydrogen to play a key role in system integration.

Offshore electrolysis is in an earlier stage of development, but there are promising initiatives. Neptune Energy (with partners) is developing an offshore electrolysis pilot on the existing offshore platform Q-13a-A.[xix] In January 2021, Siemens Gamesa and Siemens Energy announced the start of a research programme to develop electrolysers integrated into wind turbine towers.[xx]

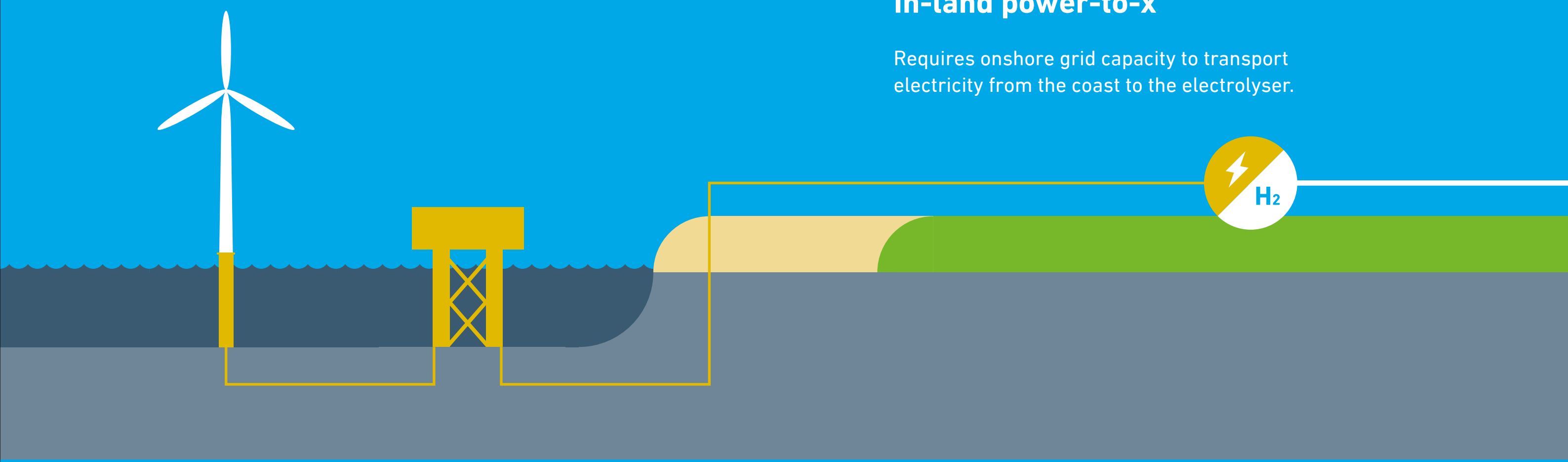
[2] Note, cost of the grid connection is socialised for these projects.

Locations for Power-to-X

It is most cost effective to locate Power-to-X capacity close to the coast.

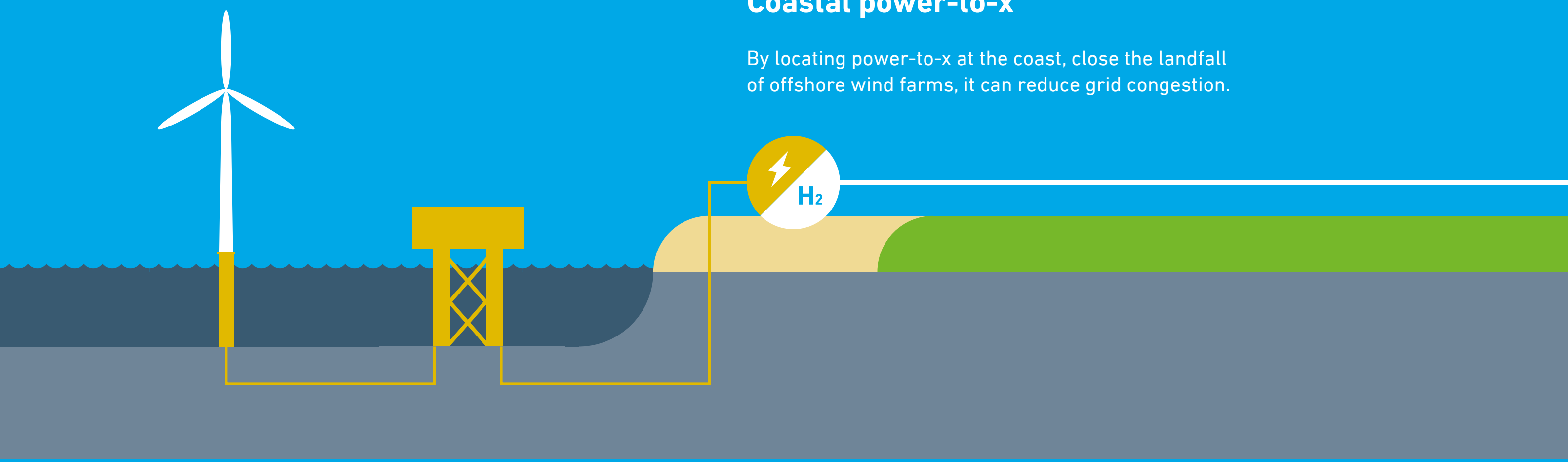
In-land power-to-x

Requires onshore grid capacity to transport electricity from the coast to the electrolyser.



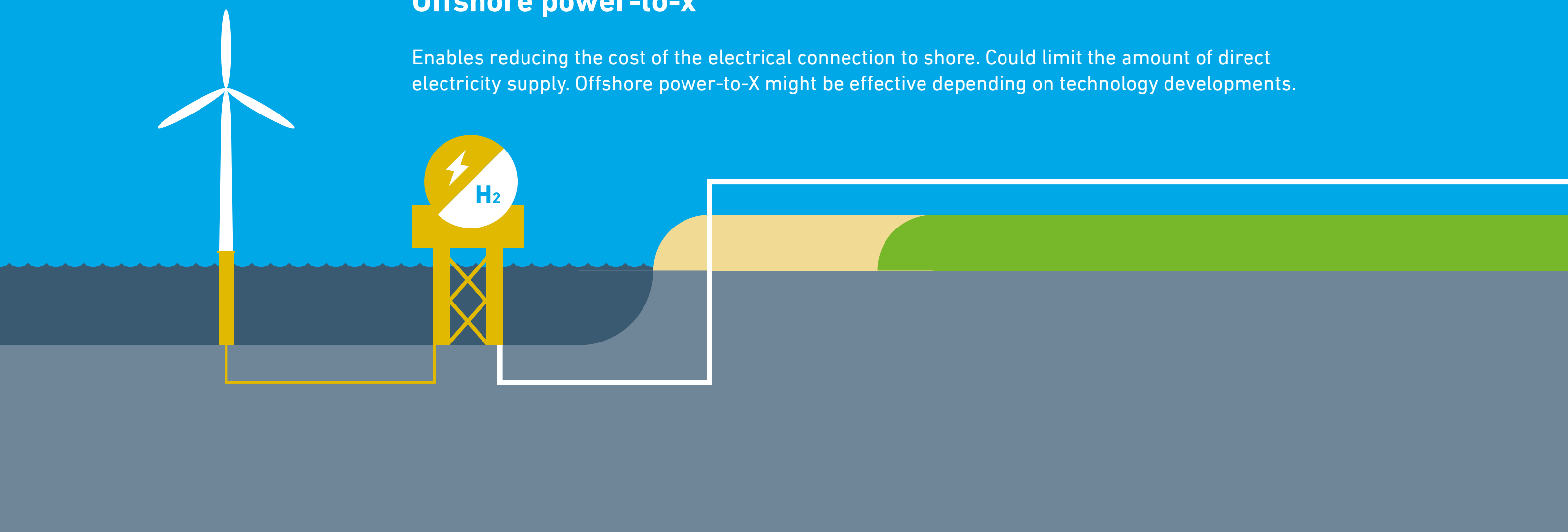
Coastal power-to-x

By locating power-to-x at the coast, close the landfall of offshore wind farms, it can reduce grid congestion.



Offshore power-to-x

Enables reducing the cost of the electrical connection to shore. Could limit the amount of direct electricity supply. Offshore power-to-X might be effective depending on technology developments.



Insights

The future decarbonised power system requires large amounts of flexibility

In a decarbonised power system based on variable renewable energy, zero-emission flexibility sources are a necessity. Our system studies show that the required capacity for flexibility is of a similar order of magnitude as the peak demand. Flexibility to increase electricity supply or to reduce demand is more difficult and costly to develop than flexibility to decrease electricity supply (curtailing supply is simple but wasteful). Depending on the timescale, several cost-effective options exist to increase electricity supply or reduce demand:

- For short-timescale flexibility: batteries, pumped-hydro and demand response
- For long-timescale flexibility: power-to-x, which can provide two-way flexibility by electricity conversion and reconversion.

Interconnection is another useful form of flexibility. Interconnection allows exporting electricity to other countries or regions in times of excess (reflected by a low electricity price) and importing electricity at times of shortage (reflected by a high electricity price). The effectiveness of interconnection in providing flexibility depends on which countries are connected to each other and whether oversupply and shortage in those countries happen at the same time. The drivers for interconnection effectiveness are the type of energy mixes and the correlation between weather patterns of different countries. For example, increasing interconnection capacity to the Nord Pool system, which has significant flexibility through hydropower, could significantly reduce flexibility needs in the connected countries.

Our modelling confirms the value of connecting diverse electricity markets: interconnecting Denmark, Germany and the Netherlands (which have similar weather patterns and electricity mixes) with the United Kingdom (UK) and Norway would increase electricity flows between the countries by more than 20 TWh per year.

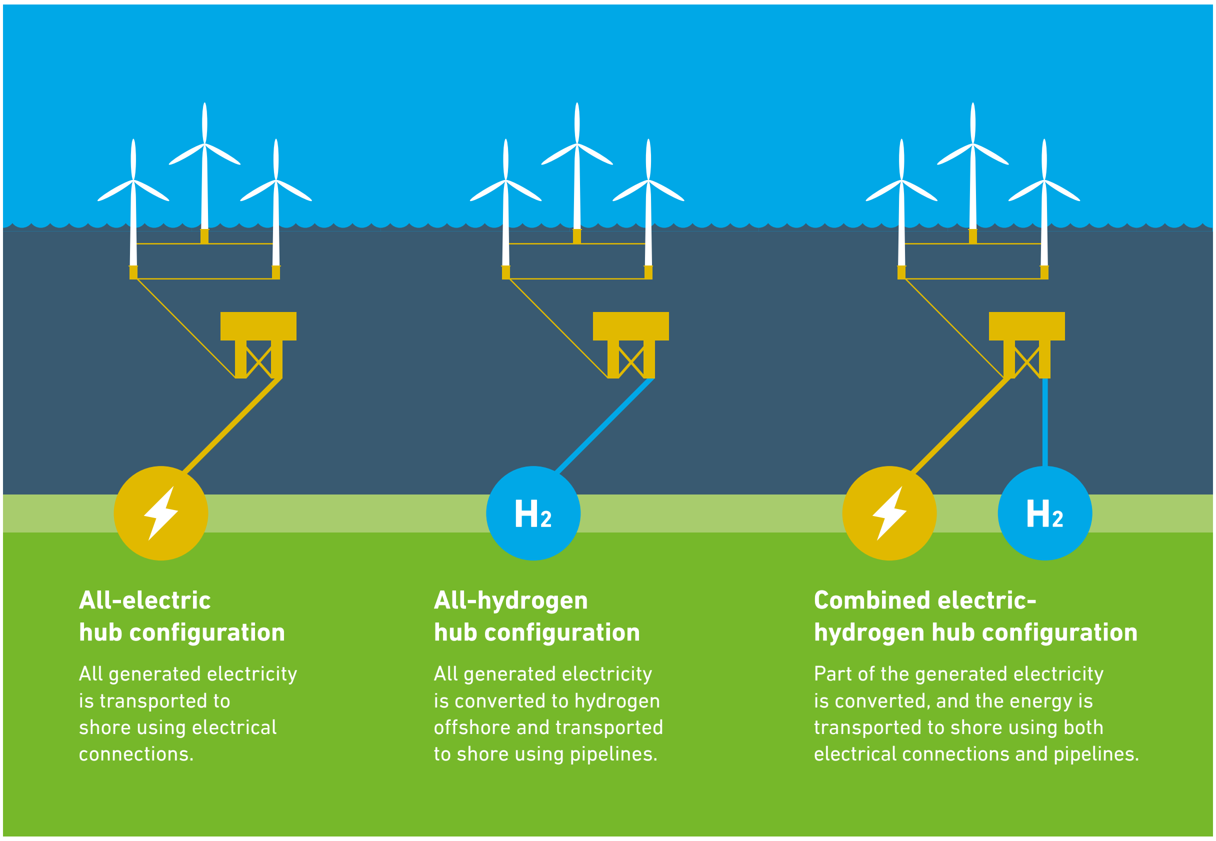
The future decarbonised power sector will still need significant (zero-emission) dispatchable generation capacity. That capacity will be of a similar order of magnitude as the peak demand, due to periods of days and weeks with very little wind and solar, even on a supranational level. However, flexibility provided by interconnection as well as demand-side response will help to reduce this capacity. We will investigate the challenge of zero-emission dispatchable generation going forward through extensive energy system studies.

Hydrogen can play a vital role in cost effectively integrating large volumes of offshore wind energy

The future system needs long-term flexibility: the ability to deliver electricity at a time when it is not sufficiently produced by renewables. We have investigated different (electricity and hydrogen) integration routes for an assumed 180 GW of offshore wind in the North Sea region in 2050[xxi]. Simply further extending and reinforcing the electricity grid (by adding long distance HVDC[3] corridors) does not solve the entire integration challenge, because mismatches in supply and demand also occur across different time scales. Renewable electricity can be converted to green hydrogen, which supports integration in multiple ways:

1. Providing long-term flexibility: by using green hydrogen for dispatchable power generation in a gas turbine or fuel cell.
2. Decarbonising non-power end-use sectors: either by direct hydrogen use or through production of synthetic fuels.
3. Reducing curtailment of renewable generation: by converting electricity surpluses to another energy carrier, particularly when power-to-gas (electrolysis) is installed in coastal regions around the North Sea.
4. Reducing grid congestion: by offering an alternative energy transportation route to electricity.

[3] HVDC: High Voltage Direct Current



Through the combination of these elements, electrolysis supports a larger and more useful roll-out of offshore wind generation compared to a situation without electrolysis.

The most cost effective of the analysed integration routes (which only considered meeting electricity demand) assumed 80-90 GW of power-to-gas[4] capacity in the coastal areas around the North Sea. This capacity allows to convert part of the offshore wind electricity to green hydrogen and to reconvert it back to electricity by using onshore gas-to-power plants when needed. Since this reconversion concerns only a modest part of the overall electricity demand, it can provide an affordable solution to achieve a 100% renewable electricity mix, despite the conversion losses. This study did not investigate how to meet hydrogen demand outside of the electricity sector.

The location of onshore power-to-gas conversion should be carefully considered. By locating it close to the landfall points of offshore wind farms, grid congestion can be reduced. From there, hydrogen will be transported to a storage facility, e.g. in a salt cavern. Gas-to-power plants can be located close to the power-to-gas convertors, or to the storage location; as electricity production through hydrogen-to-power would only take place in times of wind-and-solar shortages, grid congestion is less of a concern at those times. Conversely, hydrogen for non-power sector use should be transported to demand locations, which may be far from landfall points.

It is currently more cost effective to integrate electricity and hydrogen production than to dedicate wind energy to produce only hydrogen

Integrating electricity and hydrogen production means that renewable electricity can either be used to meet electricity demand directly or to produce hydrogen when electricity demand is lower than electricity supply. Conversely, in a dedicated configuration, all electricity from an offshore wind farm is used to produce hydrogen, at all times.

[4] For the sake of comparison, the total capacity offshore wind assumed was 180 GW. The total peak demand assumed was 390 GW.

We have developed an optimisation model to understand the total system cost of meeting the electricity demand in the Netherlands under different green hydrogen production routes. Our analysis showed that integrating new offshore wind capacity to co-produce electricity and hydrogen is more cost effective than realising new offshore wind capacity for dedicated green hydrogen production. If hydrogen is used as flexibility option to produce electricity, large conversion losses apply compared to direct electricity use. When more electricity demand is met directly, the demand for hydrogen in the power sector decreases. This reduces total conversion losses. As a result, less offshore wind capacity is needed to meet electricity demand in an integrated approach, reducing total system cost compared to the dedicated approach. When hydrogen demand in non-power sectors increases, dedicated hydrogen production may become more cost effective. We will investigate this further in a system integration study throughout 2021.

Domestic green hydrogen production plays a role in cost effective system integration, even when cheap imports are available

Hydrogen produced in southern Europe through electricity generated by solar photovoltaics (PV) could become the cheapest source of green hydrogen in Europe. If a future European hydrogen backbone is realised[xxii], domestically produced green hydrogen can face competition from this cheap imported hydrogen. In this context, we investigated the competitive position of hydrogen produced from offshore wind in the Netherlands. As hydrogen imports become cheaper, the optimum capacity of local electrolysis reduces. However, even with very cheap hydrogen imports (<1.3 €/kg), an optimised system includes substantial domestic electrolysis capacity. The reason for this is that the analysed fully decarbonised electricity system requires significant renewable electricity generation capacity. This capacity would result in many hours where generated renewable electricity would be greater than electricity demand. Domestic electrolysis enables this electricity (which would otherwise need to be curtailed) to be used to produce hydrogen.
This in turn reduces hydrogen imports.

Further integration of the electricity, gas and other energy sectors is a necessity and lowers total system costs

We have started to look beyond the integration of electricity and gas sectors alone. Energinet has developed the concept of Energy Plants[xxiii]: industrial clusters that can switch between electricity consumption and production depending on market prices. These plants couple electricity, gas and biomass sectors and are able to produce energy products, such as synthetic fuels and heat. Installing energy plants in the coastal areas around the North Sea can considerably facilitate the deployment of offshore wind and enables other sectors to decarbonise using the offshore wind potential in the North Sea.

Next steps

In 2021, we will carry out the following studies that will generate new, concrete insights into system integration:

1. **Energy landing zone study**
This ongoing study in cooperation with the Port of Rotterdam investigates optimally connecting offshore wind to shore and integration in the existing industrial cluster in the Port of Rotterdam. The study considers the design of the connection, conversion, storage assets and use of residual heat, and further investigates the concept of energy plants.

2. **Pathway infrastructure development study**
This study aims to deepen the understanding of the offshore wind integration challenges, flexibility requirements, the drivers of effectively integrating offshore wind into the energy system, and determining the design principles of the first hub-and-spoke projects.

3. **Hub configuration case studies**
We will further study specific hub-and-spoke configurations that aim to inform both the funnelling process of the NSWPH programme and the ongoing workplan under the Memorandum of Understanding between The Netherlands and Denmark.

4. **P2G Energy System Framework**
This discussion paper will explore the benefits of system integration through power-to-gas (P2G) when integrating large volumes of offshore wind into onshore grids.

5. **Supply Chain, Innovation and Technology assessment**
This study will focus on the technological readiness level (TRL) of the various technologies considered for the hub-and-spoke project as well as look at potential constraints in their supply chains.

Technical feasibility

How to design and build the physical hubs and spokes that will collect, transform and distribute energy from the North Sea.

No showstoppers on the path to technical feasibility

Hub-and-spoke projects are technically feasible: we understand the technical challenges that need to be addressed on the way to realising the first hub.

What we have learned

- We have a clear view of the toolbox of components that are needed to realise hub-and-spoke projects.
- Centralised and distributed hub concepts present different advantages and challenges. Our recommendation for the first hub is to focus on distributed hub configurations as they can align with current national political ambitions and perspectives.
- A modular and phased approach to realise a hub-and-spoke project has advantages but requires a full systemic view upfront.
- The four foundation types that we evaluated all turned out to be relevant. We now understand that the most suitable foundation type depends on the chosen locations and selected configuration
- Most electrical components needed for a hub-and-spoke project are based on established technologies.
- Energy conversion technologies are still in an earlier stage of development and scaling up requires a major effort. A key challenge is to take electrolysis technology to a gigawatt scale and make it suitable for application offshore.
- Securing stable onshore and offshore grid operation has implications on project design.

What do we need to study/learn next

- Define case studies for a set of configurations for a first hub – in consultation with relevant ministries – for the feasibility phase analyses.
- Evaluate selected case studies though a Cost Benefit Assessment.
- Conduct further research on the feasibility of technologies (in particular offshore electrolysis) and the implications of securing stable system operation.

One insight that has blown our minds

A modular and phased distributed hub concept, that consists of multiple smaller connected hubs, has technical and regulatory benefits.

What is the range of possible feasible configurations and how do they compare?

We evaluated different configurations and the required technical elements for the first hub project. We understand the critical issues and pros and cons of different configurations, and are ready to support governments to prepare for decision-making towards a first hub-and-spoke project.

Timely decisions on the design and configuration of the hub-and-spoke project are required to realise a first hub in the early 2030s. We defined different potential project configurations and mapped required technical elements. In a next step, we will work with relevant ministries to further clarify the size and location of projected wind farm developments, and will use this as a basis for more detailed technical layouts for a first hub project.

We are creating the insights and address the barriers that need to be overcome to support decision-makers taking further steps towards a first hub

Hub-and-spoke projects combine several established and a few novel technologies, and can be realised in multiple locations in the North Sea. Realising the first hub requires governmental decision-making on a final configuration. We are working to advance the first hub-and-spoke project by addressing critical issues in the development.

The results of our assessments serve as a basis for interactions with relevant national ministries and authorities to discuss the pros and cons of different potential configurations. Currently, we are supporting the collaboration of the Danish and Dutch ministries on this topic, which they are undertaking as part of their Memorandum of Understanding.

Feasible configurations for a first hub-and-spoke project depend on technological developments

As technologies considered for the first hub vary in technology readiness levels[5] (TRL), the pace and direction of technological developments will impact the techno-economic feasibility of possible project configurations. For example, the level of technological development differs between alternating current (AC) and direct current (DC) electrical technology and between different hydrogen production (electrolysis) technologies. We have assessed the TRL levels of those technologies and have identified which further development is needed for implementation in a hub.

[5] Technology Readiness Level (TRL) is a methodology to systematically assess the maturity level of a specific technology, the levels range from 1 to 9.

Situation

Hub-and-spoke technologies are developing but further research is required

To realise offshore wind roll-out at the scale that is required, we need different technologies than current common practice. Most offshore wind farms are currently connected to shore using alternating current (AC) electricity cables. While cost efficient, this technology can only be applied for sites that are relatively close to shore (up to about 100 km). By using direct current (DC) electrical connections, it is possible to connect sites hundreds of kilometres from shore. In addition, the power that can be transported through a single DC cable is greater than through an AC cable. The DC technology has become mature, and has been applied to most German offshore wind farms.

The hub-and-spoke concept, where several countries are interconnected (using DC electrical cables) through a hub, requires technology that is not yet commercially available. In particular, DC circuit breakers, protective devices that disconnect lines in case of faults, need to be further developed. The research programme PROMOTioN[xxvi] has produced valuable insights into the technological readiness of these kinds of components.

The hub-and-spoke concept considers energy conversion through electrolysis, either onshore or offshore. While onshore electrolysis on a small scale has been used for decades, further research and development is required for the application on a GW-scale, as well as the application offshore. Initiatives have been announced to study offshore electrolysis, but no operational projects have been realised yet.

The Danish Government has made progress towards project definitions for a first energy hub

In February 2021, the Danish Ministry of Climate, Energy and Utilities announced that they will initiate plans to construct the first energy hub in the North Sea by the early 2030s. This is the first actual development of an energy hub. The hub will be situated approximately 80 kilometres off the coast of Jutland. The initial capacity is 3 GW (with a hub footprint of about 120,000 m2) and the Danish plans envisage the possibility to expand this to 10 GW in later stages. The substructure of the hub will be caisson-based.

Insights

We analysed the feasibility of different hub-and-spoke configurations

We identified and jointly evaluated potential configurations for a hub-and-spoke project in the North Sea. Our decision-making framework covers a wide "design space": i.e. different water depths, distances to shore, hub types, electrical configurations and Power-to-X options. We are increasing our understanding of the techno-economic drivers for the first hub-and-spoke project. These pre-feasibility activities and our interactions with relevant ministries support the funnelling process towards the feasibility phase.

Centralised and distributed hub concepts present different advantages and challenges

We have defined two hub-and-spoke concepts for the first hub, a centralised hub concept and distributed hub concept. The distributed hub concept is more aligned with national developments and faces fewer regulatory barriers *(see Regulation & Market design)*. Our recommendation for the first hub is to focus on distributed hub configurations as these align with current national political ambitions and perspectives in North Sea countries. The Danish energy island, for example, is based on a similar philosophy and could fit well into a distributed hub-and-spoke concept in the North Sea. In a next phase, offshore wind areas should be identified by governments of the respective countries, which are suitable and attractive.

The most suitable hub foundation type strongly depends on the selected location and configuration

We evaluated four different foundation types based on their techno-economic characteristics and suitability for a hub-and-spoke project: a caisson island, an artificial sand island, a jacket foundation and a gravity-based structure. The results showed that all four foundation types are technically feasible; the most suitable foundation strongly depends on the selected location (which determines water depth) and the size of the hub.

A sand island is expected to become a potential option only for projects from the mid-2030s onwards, due to its longer development time. Like islands, gravity-based structures provide the possibility for a modular development of a hub.

Key concept | Centralised and distributed hubs

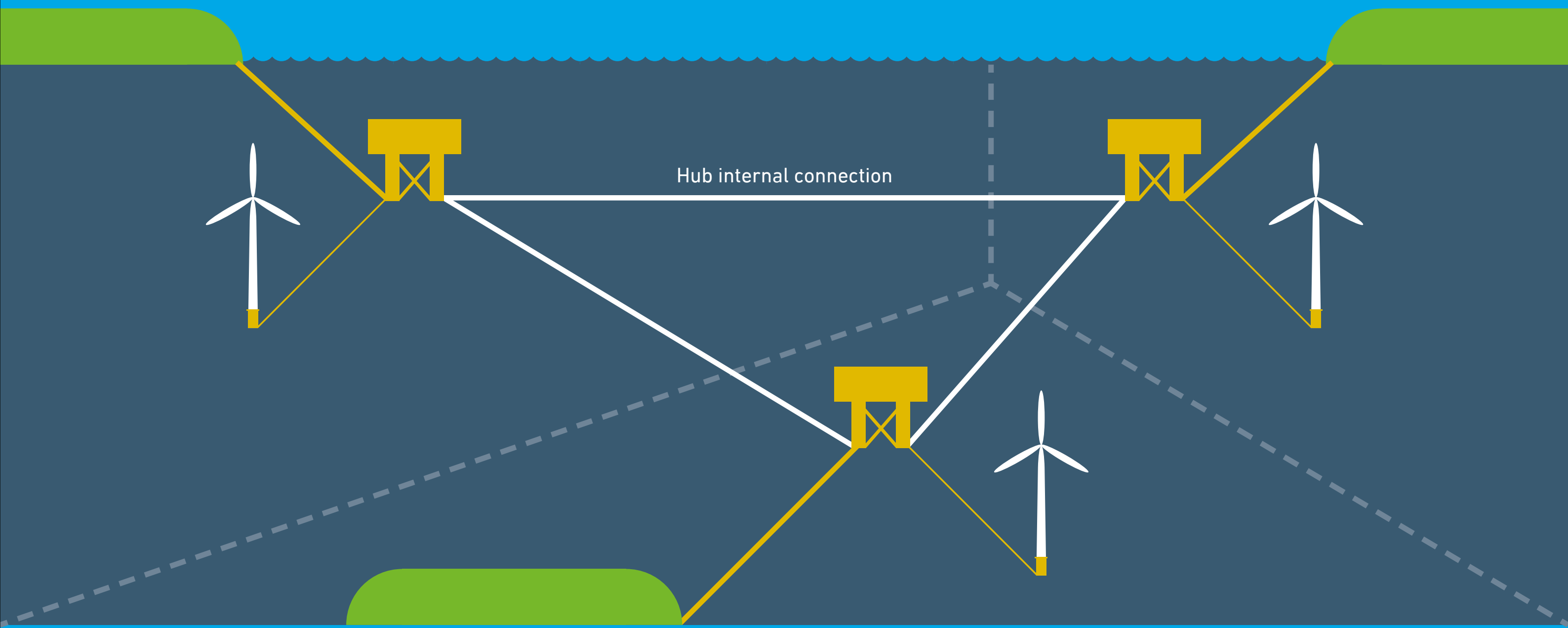
A centralised hub concept consists of a single large hub located within the exclusive economic zone (EEZ) of a single country with interconnectors to different countries.

A distributed hub concept comprises multiple, smaller hubs in the EEZs of multiple countries with interconnections between the hubs and countries.

Two hub-and-spoke concepts

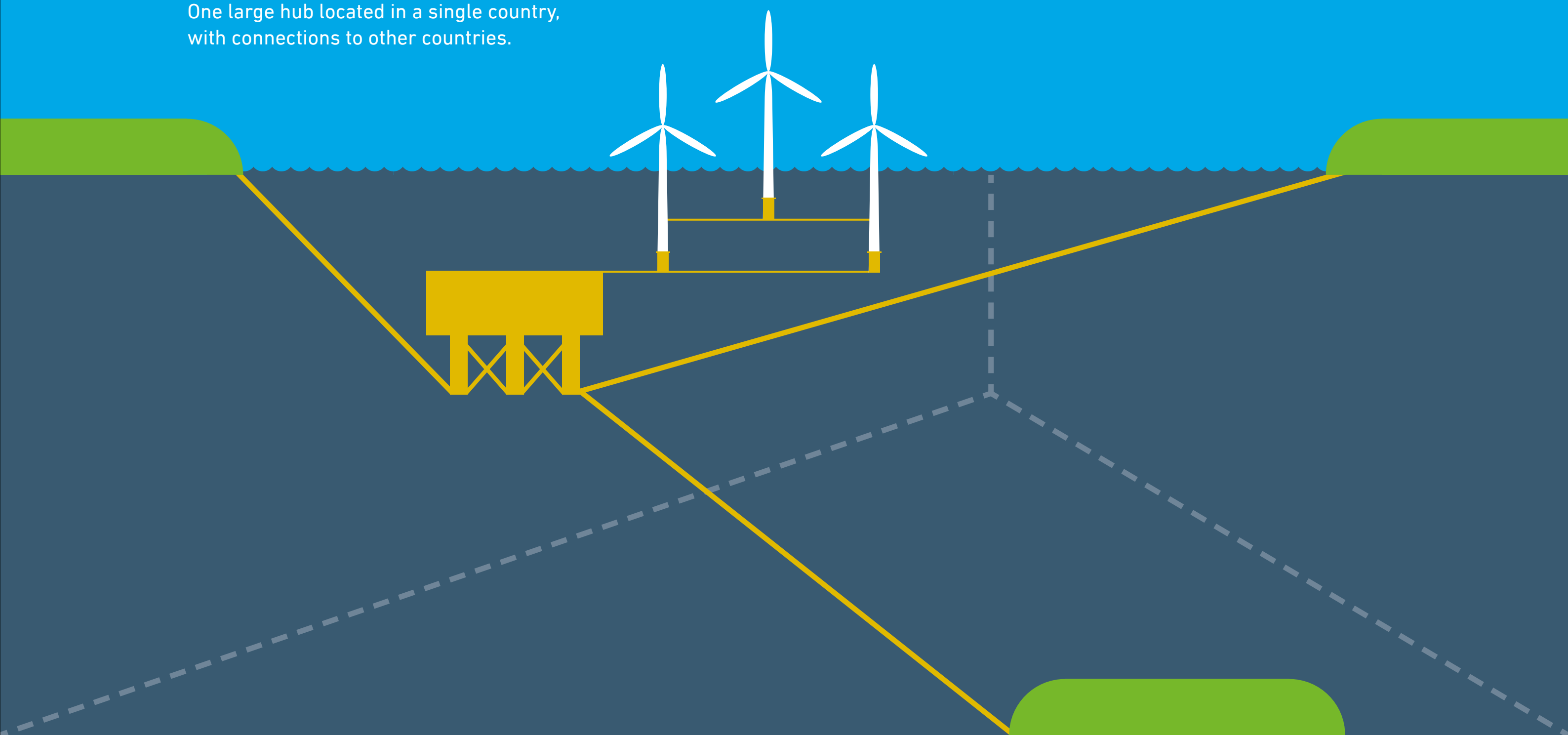
Distributed hub

Multiple smaller hubs in the EEZ
of different countries.



Centralised hub

One large hub located in a single country,
with connections to other countries.



	Caisson island	Sand island	Jacket	Gravity-based structure
Water depth limitations	larger 25m	larger 40m	larger 45m	larger 100m
Construction time substructure (yrs)*	3-4	6-8	3-4	3-4
Size limitations	up to 6 GW	up to 36 GW	up to 2 GW	up to 6 GW
Phasing & modularity	no	not for hub	yes	yes
Maturity	middle	middle	high	units - high linking - middle
Footprint on seabed	high	high	low	middle
Accessibility	limited sheltered	sheltered	unsheltered	unsheltered

*Construction durations are indicative, and will vary according to capacity and local environmental situation.

Development of a hub-and-spoke project based on a modular and phased approach has advantages but requires a full systemic view upfront

Developing the hub-and-spoke project in pace with the offshore wind farm capacity and interconnectors that connect to it, limits anticipatory investments and creates flexibility. This phased approach requires a design that is modular, i.e. the hub can be constructed in multiple fully functional modules. It is however important to consider all project phases (and thus all expected capacities) from the start. Adding additional capacity after the design is finalised may not be feasible and is likely cost inefficient. Modular design of a hub is not straightforward; we will further define and assess the steps needed to ensure an effective modular and phased development of a hub-and-spoke project.

Securing stable onshore and offshore grid operation has implications on project design

If, for example, a 12 GW hub operating at full capacity fails and loses all capacity, it could result in black-outs in the connected countries – and possibly beyond. To ensure stable grid operation, the hub design must include measures that avoid losing its complete capacity through a single event. We started investigating the implications of a hub-and-spoke project on stable grid operation both on- and offshore;

- The hub-and-spoke system should be designed based on onshore grid operational requirements: For instance, the maximum total capacity that is allowed to fail in a single event. Individual electrical connections in the hub-and-spoke project could therefore be selected with lower capacity ratings, if required due to onshore grid restrictions. Currently there are national restrictions that limit the maximum size of a single potential failure; in Denmark this is 700 MW, in the Netherlands 1,000 MW and in Germany 1,400 MW. This means that to realise the envisaged 2 GW interconnections, a bi-polar connection including two separate, largely independent bays is required. This approach allows the system to limit outages as much as possible to approximately 1 GW, which would be within the limits of the Netherlands and Germany (but still above the limit of Denmark).

- When using HVDC technology to connect the hub, HVDC circuit breakers will become a likely necessity to ensure stable grid operation. These components are not yet commercially available but are under advanced development.
- Upscaling of electrolysers and safety aspects with respect to offshore and onshore hydrogen production should also be further assessed to identify their impact on security of supply in the electricity system.

The optimal capacity of ‘internal’ hub interconnectors for distributed hubs may result in some internal congestion

Optimal dimensioning of connections – both in terms of connected countries and hub ‘internal’ interconnectors – is important for cost efficiency. Internal interconnectors are those present between the modules of a distributed hub configuration, and connect the hubs with one another. We performed power market and load flow modelling to quantify the flows on hub-and-spoke internal connectors given certain interconnector capacities between the hub and selected countries. We investigated several project configurations to understand the optimal hub-internal connection capacity required, by comparing (1) a distributed hub concept connecting Denmark, the Netherlands and Germany and (2) a distributed hub concept that additionally connects UK and Norway. The addition of United Kingdom and Norway to the hub project adds greater market and price diversity, which results in an increased overall utilisation of the hub transmission assets.

We investigated how to optimise the internal interconnectors: it is a trade-off between the cost of the connections and the amount of internal congestion. Our results show that the optimum does not necessarily lie in avoiding all congestion (in technical terms, realising a “copper plate”). In most periods a lower capacity can be sufficient based on the utilisation levels, but a minimum capacity is set by compliance with security of supply standards.

Our cost model will enable comparing different hub-and-spoke project configurations to inform design choices

We developed a cost model to compare different hub configurations based on economic selection criteria. The first results indicate that the costs of distributed hub configurations are slightly lower than those of centralised configurations. This is because of the shorter average distance between the offshore wind farms and the hub, requiring shorter array cables. Generally, the simplest configurations have the lowest cost, but there is additional work to be done to fully understand the full benefits of each configuration. Therefore, we cannot yet conclude on what is the optimal hub design. We will refine our cost model in the next phase to feed into the cost benefit analysis *(see Costs and Benefits)* of different shortlisted configurations.

TRLs of electrical and conversion technologies vary; most electrical elements needed for a hub-and-spoke project are based on established technologies

We identified a list of expected components required for the electrical system of hub-and-spoke project configurations. Most of these required electrical elements are based on established technologies;

- For high voltage AC systems, all elements are common technology and have a technological readiness level (TRL) of 9.
- For high voltage DC systems, point-to-point connections are well-known. We currently expect that a voltage of 525 kV will be used for the hub-and-spoke project, and bi-pole electrical cables will be used with a combined capacity of 2 GW.
- Further investigation of HVDC circuit breakers is still required. At the end of 2020, they had a TRL of 7. As HVDC circuit breakers are currently already applied in China, there seem to be no technical showstoppers. We expect that this technology will achieve TRL 9 in time for the first hub and can be included in the design processes.
- Investigation regarding standardisation and inter-operability requirements for HVDC systems is still needed to enable the realisation of multi-terminal, vendor-independent HVDC systems, reached via cooperation between TSOs and manufacturers.

For wind turbines within 25 km of a hub, direct connections with 66 kV cables are considered the optimal solution. Further research should assess the suitability of direct connections at larger distances. We did not yet analyse potentially required onshore electricity grid reinforcements that come with the integration of large additional amounts of offshore wind energy. This will be analysed throughout the further development stages of the concept towards realisation of an actual first hub.

Energy conversion technologies are still in an earlier stage of technical maturity and scaling up requires a major effort

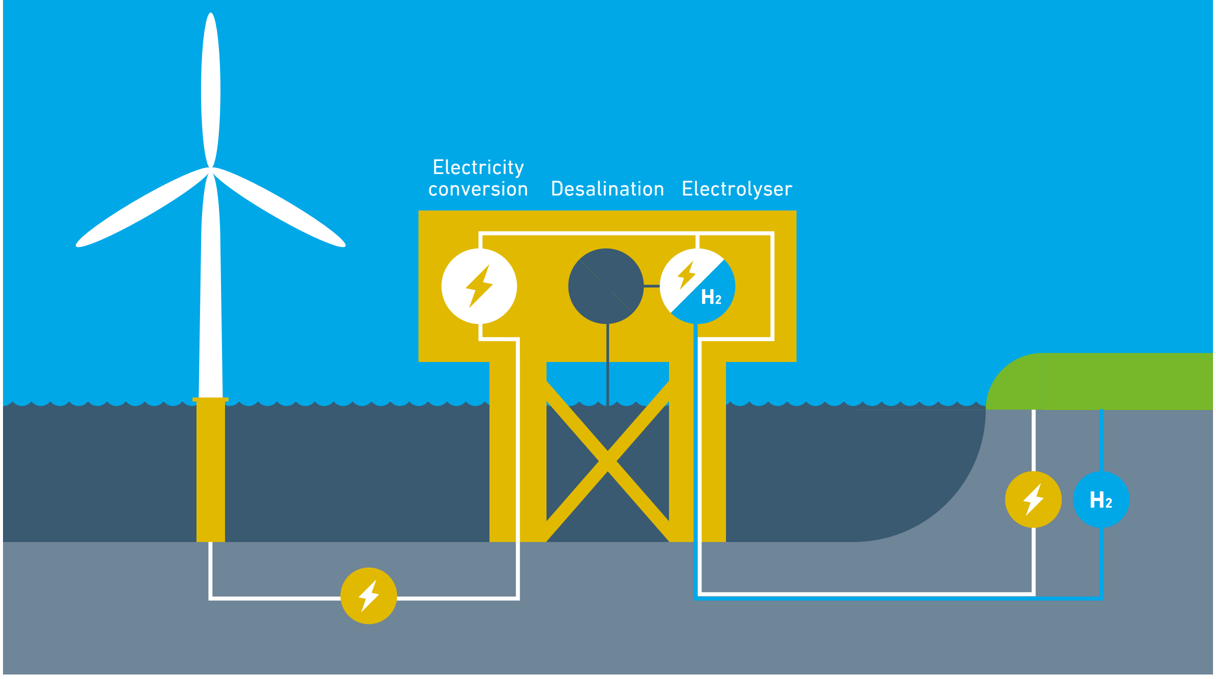
Energy conversion technology – such as electrolysis to produce hydrogen from electricity – could become part of hub-and-spoke projects as it can play an important role to integrate large amounts of offshore wind in the energy system. Both onshore and offshore conversion are being investigated. Our initial findings did not show clear showstoppers for either, but there is no demonstration of the required technology at the gigawatt scale yet[6], nor operational demonstration of application offshore.

Most of the components for electrolysis show a relatively high technological readiness level (TRL) at smaller scales. Major work is still required to scale-up and demonstrate readiness at the scale and conditions associated with the hub-and-spoke concept.

Our investigations into different conversion options are at an earlier stage than the electrical aspects. We have not yet identified the optimal location of conversion (on- or offshore) or the type of electrolyser that would be best suited for a hub-and-spoke project, although Proton Electrolyte Membrane (PEM) and Alkaline electrolysers seem most promising for the first project. We will develop more detailed insights on individual components, conversion processes and cost estimates in the coming period.

Power-to-X

Power-to-X in its most basic form means electrolysis of water to produce hydrogen. This can be done offshore, in which case salt needs to be removed from the sea water through a desalination process. It is possible to transport both electricity and hydrogen to shore.



[6] Note, in chlorine chemistry electrolysis has been applied at capacities exceeding 100 MW, however with different types of materials.

Next steps

In 2021, we will analyse specific case studies, refine our models and conduct more detailed research.

1 **Case studies**
Define case studies for a set of suitable configurations for a first hub together with relevant ministries. We are supporting the Danish and Dutch ministries with this effort throughout 2021 under their MoU framework. We stand ready to share our insights with other governments and within the frameworks of other cooperation agreements between North Sea countries.

2 **Model development**
Further develop and refine our models to enable more detailed techno-economic comparison of project configurations.

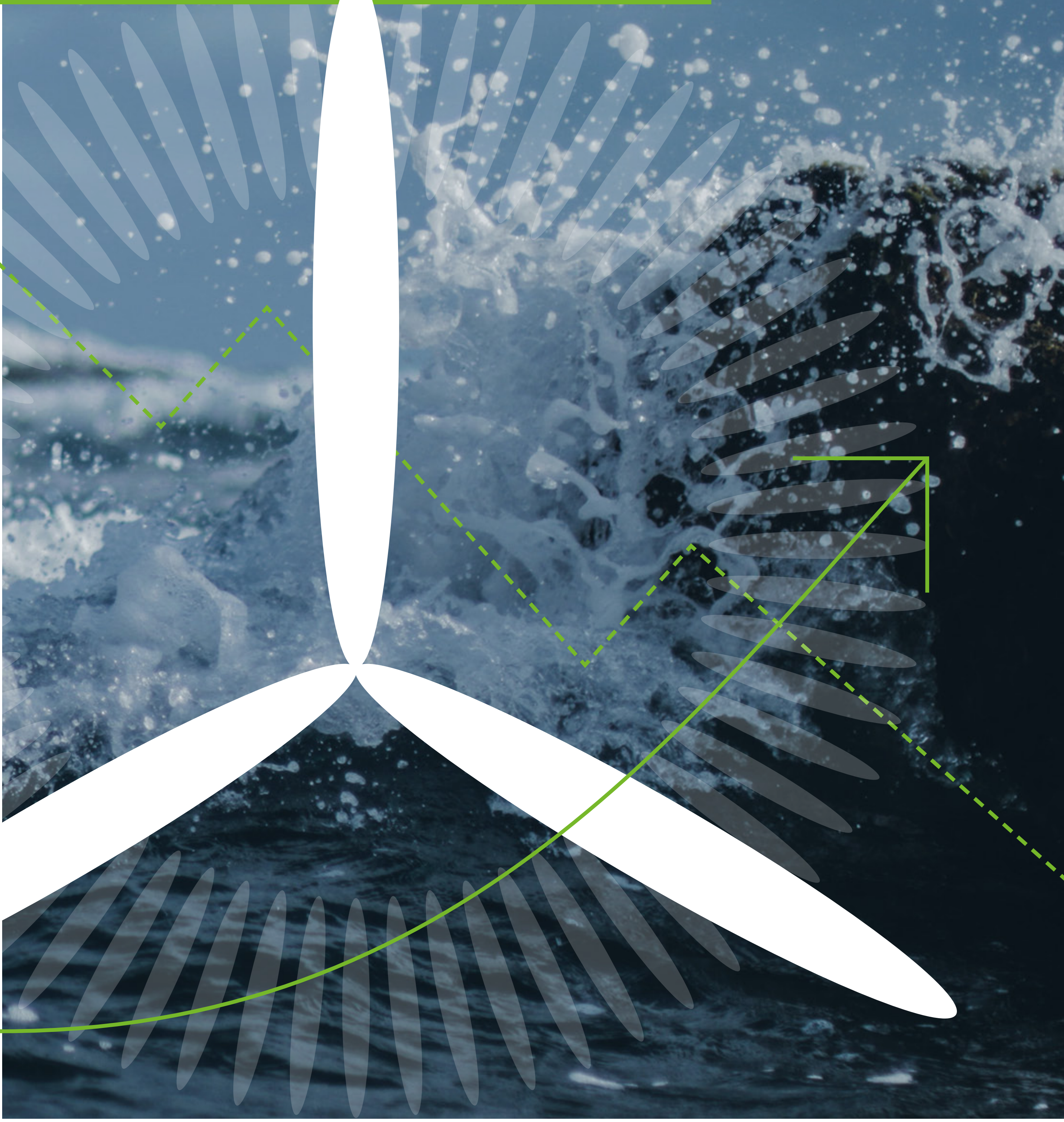
3 **Research**
Conduct further research into the feasibility of technologies and stable system operation.

4 **P2G Energy System Framework**
This discussion paper will explore the benefits of system integration through power-to-gas (P2G) when integrating large volumes of offshore wind into onshore grids.

5 **Cost & benefits**
Assess case studies with the developed CBA framework *(see Cost & Benefits)*.

Cost & Benefits

How to ensure that the chosen solution maximises benefits for society and climate while minimising costs and distributing them fairly between countries and stakeholders.



We need a new way to analyse cost and benefits

The cross-sectoral, transnational and hybrid character of a hub-and-spoke project requires a new cost benefit assessment framework that can show the societal benefits of different concepts.

What we have learned

- Steps are needed to develop a tailored integrated CBA guideline for transnational hub-and-spoke projects with an energy system approach rather than a single-sector view.
- Many possible configurations of the hub-and-spoke concept exist, leading to a large number of alternative project configurations. This complicates the analysis.
- A new approach to define reference cases for the comparison of project alternatives is required due to the scope and functionality of a hub-and-spoke project.
- To capture the main costs and benefits of a hub-and-spoke project, interdependencies between the project's building blocks must be accounted for.
- Scenario analyses are key to the CBA of hub-and-spoke projects to deal with uncertainty.

What do we need to study/learn next

- Finalise an integrated CBA framework, including tools needed, scenario definitions, project alternatives and reference system.
- Kick-start stakeholder dialogue on a suitable integrated CBA approach for transnational hub-and-spoke projects.
- Conduct the first CBA analysis for a handful of hub-and-spoke project configurations in the second half of 2021 to obtain initial results to inform the funnelling process to more concrete project configurations.

One insight that has blown our minds

Current single-sector approaches to societal cost benefit analyses do not fit a hub-and-spoke project. A tailored integrated CBA guideline is required.

How can we develop a new internationally accepted perspective for a suitable CBA framework for hub-and-spoke projects?

The hub-and-spoke concept combines offshore wind generation and connection, interconnection and energy conversion of which the societal benefits need to be captured and interdependencies need to be considered. We developed guiding principles to change the perspective on current CBA approaches to kick-start a stakeholder dialogue.

A societal cost benefit analysis (CBA) framework identifies the societal benefits and costs of large energy infrastructure projects. We work to develop a suitable and integrated CBA framework able to capture the benefits and unique characteristics of hub-and-spoke projects. This will ensure we can identify those project configurations to integrate large amounts of offshore wind that bring the highest value to European society.

Action should be taken now to develop a new integrated CBA approach

A hub-and-spoke project is not only expected to bring benefits to North Sea countries directly connected to the project, but also to countries located further from the North Sea and to European society as a whole. A societal cost benefit analysis (CBA[7]) identifies the costs and benefits of project alternatives and enables identifying the project with the highest value and the highest expected return to society. It is often used to assess future policy decisions or large energy investments. In addition, a CBA could facilitate a first step towards enabling the distribution of costs and benefits between countries (cross-border cost allocation).

A positive societal CBA outcome is a prerequisite to realise large energy infrastructure projects, like the hub-and-spoke concept: societal benefits must outweigh the societal cost of the investment.

Due to the cross-sectoral, transnational and hybrid nature of hub-and-spoke projects, we need to think differently about the required CBA framework. Existing CBA approaches do not enable to fully identify the key benefits of such a project. We believe action should be taken now to develop a new integrated approach for a CBA framework, which considers the synergies of integration, on an international and sectoral level. Therefore, we currently undertake steps to develop such a suitable CBA framework.

[7] In this paper any reference to CBA refers to a societal CBA.

Situation

Existing CBA frameworks for energy infrastructure projects focus on single projects in single sectors

At a European level, CBA guidelines exist for large energy infrastructure projects. The Transmission System Operator networks ENTSO-E[xxv] and ENTSOG[xxvi] have developed CBA guidelines for electricity and gas infrastructure development, respectively. These guidelines focus on projects interconnectors or pipelines with a single functionality (transmission or, in some cases, storage) in a single sector (electricity or gas). Additionally, Member States often have national CBA guidelines to facilitate and inform national infrastructure planning processes.

An adaptation of the ENTSO-E CBA guideline was used to analyse an initial all-electric configuration of the North Sea Wind Power Hub as part of the ENTSOE TYNDP process, resulting in the award of PCI status as a cross-border project of common interest at a European level.[xxvii]

Hub-and-spoke projects have unique characteristics that require a new CBA approach - current CBA frameworks are not suited to capture their integrated societal benefits

Hub-and-spoke projects introduce new combinations of sectors and functionalities within a single project:

- Transnational: by connecting multiple countries through a hub-and-spoke concept
- Hybrid: by combining interconnection with the connection of offshore wind
- Cross-sector: by integrating different energy sectors and energy carriers

Existing CBA guidelines are not able to capture the societal benefits that arise from these specific characteristics of a hub-and-spoke project.
Over the last few years, ideas for a suitable CBA methodology have progressed (e.g. in the PROMOTioN project[xxviii] and the European Commission study on recommendations for an integrated framework for the financing of joint (hybrid) offshore wind projects[xxix]). The EC proposal for the revised Trans-European Networks for Energy (TEN-E) regulation, published in December 2020, emphasises the need for harmonised system-wide cost-benefit analysis at EU-level for Projects of Common Interest. Under the proposed regulation, ENTSO-E and ENTSOG would be required to publish and submit their harmonised methodologies by 16 November 2022 to the Member States, the EC and the Agency for the Cooperation of Energy Regulators (ACER).

A clear and transparent societal CBA enables cross-border cost allocation (CBCA)

The benefits and costs stemming from a hub-and-spoke project might not be evenly distributed between different countries and stakeholders. A suitable CBCA guideline will help to distribute cost and benefits across impacted stakeholders and countries. Before the CBCA guideline can be developed, a CBA guideline is required.

Key concept I Societal cost benefit analysis (CBA)

A societal CBA is used to assess the costs and benefits of a project to society. Comparing the results of different alternative projects to a reference case allows to identify the project that results in the highest benefits compared to cost to achieve a certain goal, e.g. large-scale integration of offshore wind. A societal CBA requires a clear set of guidelines to consistently evaluate alternative projects. These include guidelines for the definition and scope of project alternatives, the reference case, the geographical scope of analysis, the cost and benefit indicators that should be evaluated, the definition of scenarios and the tools and assumptions to use for calculations.

Insights

Steps are needed to develop a tailored integrated CBA guideline for transnational hub-and-spoke projects with an energy system approach rather than a single-sector view

A hub-and-spoke concept combines three building blocks; offshore wind generation and connection, interconnection and Power-to-X. A new CBA framework is required to quantify the societal benefits that each of these elements bring and to capture their interdependencies.

The ENTSO-E guideline provides a good starting point for the development of a CBA framework with a more systemic view. We aim to be consistent with both the ENTSO-E and national guidelines wherever possible. We recommend special attention to the following elements in the design of a more tailored CBA framework[xxx]:

- deal with new sectors and technologies not yet covered in the ENTSO-E methodology,
- achieve an overarching system focus to capture the cost and benefits of hub-and-spoke configurations,
- account for interdependencies between renewable energy production and infrastructure, and
- use a wide geographical boundary for the quantitative assessment, at least covering the pan-European area.

Many possible configurations of the hub-and-spoke concept exist, leading to a large number of alternative project configurations, complicating the analysis

The CBA methodology will provide insight into the configuration for large-scale wind integration that generates the highest benefits to European society as a whole compared to the societal costs. Many possible configurations of the hub-and-spoke concept exist based on hub location, foundation type, wind farm capacity, level of interconnection and electricity conversion approaches.

- we intend to develop a limited number of project configurations through sensible combinations of the hub-and-spoke elements to cover the possible spectrum of options, so called factuals.
- we consider it important to analyse a national approach for offshore wind roll-out as the counterfactual to internationally coordinated hub-and-spoke configurations, so called counterfactuals.

A new approach to define a reference case for the comparison of project alternatives is required

CBA compares alternative project configurations to a reference case (baseline). We intend to compare each alternative hub-and-spoke project (factuals) to their respective reference case (counterfactual). Where reference cases should reflect less internationally coordinated and integrated systems than project alternatives. Given the uncertainty in timing and plans for future developments of the North Sea energy system, defining reference cases is challenging. A decision on reference cases is still required. Our goal is to align and agree on the reference cases with policymakers.

Main elements of a societal cost benefit analysis

A CBA for hub-and-spoke projects needs to define guidelines for each of these elements.

To capture the main costs and benefits of a hub-and-spoke project, interdependencies between the project's building blocks must be accounted for

The current ENTSO-E CBA guideline gives an extensive overview of possible project benefits and enables capturing the main benefits of hub-and-spoke project configurations. Therefore,

- We plan to use the indicators from the ENTSO-E CBA guideline as a starting point,
- we intend to quantify the socio-economic welfare indicator to enable distribution of benefits between countries and stakeholders,
- and we want to ensure to capture interdependencies between PtX, offshore wind generation and interconnection in the socio-economic welfare indicator.

Both the investment and operational costs of the project are included in the CBA. The main challenge is defining the project boundaries and deciding on which costs fall within the scope of a hub-and-spoke project. This pertains, in particular, to

- the in- or exclusion of onshore grid reinforcement costs. As these costs might differ substantially between project alternatives, these should be included to some extent.
- the in- or exclusion of offshore wind farm costs. Interdependencies between the offshore grid design and the cost of offshore wind farms should be accounted for.

Scenario analyses are key to the CBA of hub-and-spoke projects to deal with uncertainty

Scenario analyses of project configurations are important to gain an understanding of the robustness of the CBA outcomes with respect to uncertainties. Scenarios can be defined to capture uncertainty in policy, external developments, and technology. We consider it important that employed scenarios cover both offshore and onshore developments and that they interlink gas and electricity developments on demand, infrastructure and supply sides.

Next steps

For the upcoming phase of the project over the coming 6-12 months, we have identified the following actions to enable moving to the feasibility stage.

1 **CBA framework**
Finalise a CBA framework including tools needed, and define scenarios, project alternatives and reference cases.

2 **Models**
Develop the required energy modelling tools to conduct the analyses.

3 **Assessment**
Conduct the first CBA analyses on selected hub-and-spoke configurations in the second half of 2021.

4 **Initial results**
Finalise the CBA framework and obtain initial results to inform the funnelling process to move towards more concrete hub-and-spoke configurations.

Regulation & Market design

How to ensure a stable and reliable investment climate by adapting regulation and creating an efficient market design.

International regulatory cooperation and decision-making is essential

The timeline to realise the first hub project in the early 2030s is critical. Important steps in international cooperation are being taken and need to continue.

What we have learned

- We have identified a critical timeline for decisions on key policy topics to realise the first hub in the early 2030s: the Topical Agenda.
- Smooth decision-making by policy makers requires an integrated timeline that considers interdependencies across key regulatory and policy topics.
- Both home market and offshore bidding zone market setups have advantages and disadvantages in terms of regulatory compliance and implementation.
- The relative effects of the selected market setup on socio-economic welfare are small but potential benefits of an offshore bidding zone market setup are enhanced when more diverse markets are connected through the hub-and-spoke project.

What do we need to study/learn next

- Continue to develop evidence-based discussion papers tackling new and emerging regulatory topics, including on governance models and PtX regulatory frameworks.
- Engage with policy makers on key decisions following the critical timeline developed under the Topical Agenda

One insight that has blown our minds

Smooth decision-making by policy makers requires an integrated timeline that considers interdependencies across key regulatory and policy topics.

How can we ensure that governments make the necessary decisions at the right time?

We have identified an integrated decision-making timeline to realise the first hub in the early 2030s that considers interdependencies across key regulatory and policy topics. We will support the decision-making process and will be ready to provide insights timely, to facilitate keeping the necessary pace.

Decisions on key regulation and policy are crucial to enable the ambitious timeline towards the first hub-and-spoke project. We developed a critical decision-making timeline and are working on further insights on regulatory and market design topics.

Timely policy decisions are critical for project success

Current national and EU-level policies and regulatory frameworks are not suited to govern hybrid, transnational, cross-sector hub-and-spoke projects. We need a coordinated approach to long-term policy targets, and a robust and consistent regulatory framework among all North Sea countries. This renewed approach to energy system planning will be fundamental for the successful roll-out of offshore wind and grid infrastructure.

Before a project investment decision is taken, decisions or clarity on policies and regulation are required to provide investment certainty and to reduce risks. Delayed policy and regulatory decisions will impact project realisation timelines, making it more difficult to meet CO_2 reduction targets in a timely and cost-efficient manner. Therefore, we have developed a critical timeline for decision-making on key policy topics. This will facilitate a structured discussion on international alignment and timely decision-making at both Member State and EU level.

Large-scale offshore hub-and-spoke projects have lead times of 10-15 years after the project is scoped and embedded in offshore wind development plans. Developers, TSOs, policy makers and regulators need to start collaborating now to make timely decisions on key policy and regulatory topics to realise a first hub in the early 2030s. We intend to pro-actively engage with stakeholders to ensure addressing critical topics timely to not only enable the first hub in the most efficient way possible, but also enable the subsequent large-scale roll-out of offshore infrastructure in Europe. We stand ready to support policy makers throughout their decision-making timeline and share our expertise.

Situation

While many policy and regulatory processes are already underway in the North Sea countries and at the EU-level, many topics still lack clarity or direction

As explained in the Vision chapter, 2020 was a pivotal year for initiatives on hybrid projects, both at Member State and EU levels. Several North Sea countries defined post-2030 offshore wind targets and Denmark is developing a first offshore energy hub by 2030. At the EU level, the Offshore Renewable Energy Strategy and the proposed revision of the TEN-E regulation defined a crucial role for hybrid projects in the North Sea, and proposed initial guidelines on market setup, CBA framework development, financing of assets and joint project planning. The subsequent Council conclusions identified the need for a comprehensive approach to enable national and cross-border offshore energy projects.

Important first steps in international cooperation between North Sea countries are being taken but need to accelerate to move towards project development

International cooperation and alignment on policy and regulatory topics is crucial to develop joint offshore projects. Throughout 2020, several North Sea countries took important initial steps towards transnational cooperation. The NSWPH consortium is currently supporting the cooperation between the Danish and Dutch governments to execute the workplan as defined under their Memorandum of Understanding signed on 14th of December 2020. This workplan aims to identify topics for international policy alignment and conduct techno-economic analysis throughout 2021.

Furthermore, the Netherlands and Germany signed a Joint Declaration of Intent to further cooperate in the planning and realisation of grids and electricity transmission. Denmark and Germany signed a Letter of Intent on Jointly Analysing Joint and Hybrid Offshore Renewable Energy Projects between the countries. In addition, the North Sea Energy Cooperation countries (NSEC) agreed in 2019 on a joint 2020-2023 workplan with one of its support groups focussing on hybrid and joint projects.

Insights

We have identified a critical timeline for decisions on key topics to realise the first hub in the early 2030s: the Topical Agenda

We have developed a structured approach to address key policy and regulatory topics, so that key decisions can be made on time to realise a first offshore hub. Five priority topics in the Topical Agenda require decisions to ultimately arrive at a full enabling framework that provides sufficient investment certainty to project stakeholders:

1. **Main Principles |** Framework to kick-start initiation of the first hub and define guiding principles, including post 2030 offshore wind targets, offshore wind development zones, principles for market arrangements, governance models, assessment of costs and benefits, and cost sharing.
2. **Scope |** Specified scope of the first project (e.g. location, size, technology), hubs and interconnectors, governance models, as well as the sequencing of investments.
3. **Cost & Benefits |** An agreed framework and outcome for assessing (and sharing) costs and benefits between North Sea countries, and the outcome of the assessment.
4. **Investment Framework |** National and international discussions on the investment and regulatory framework governing the project, including support schemes, financing, cost recovery and an energy market outlook.
5. **Contractual Implementation |** Legal framework and contractual agreements that enforce the principles and decisions from the other topics and provide certainty to regulators and developers.

Decisions on these topics must be made ahead of, or in parallel to, the scoping phase of projects to enable a timely investment decision; i.e. all key decisions and agreements related to the scope of the First Hub must be in place roughly a decade before the hub delivers power to shore for the first time.

Smooth decision-making by policy makers requires an integrated timeline that considers interdependencies across key regulatory and policy topics

Tackling the five priority topics in an integrated manner is important as they are highly interdependent: each topic is input to others. In the Topical Agenda we account for these interdependencies to avoid jeopardising project planning and development timelines, whilst allowing for the most efficient process possible. This will ensure policy options and decisions are weighed in their full context to prevent lock-in and account for flexibility in later stages of decision-making. Each key topic consists of multiple subtopics, each of which dives into detailed regulatory themes. Decision-making for each subtopic will be made either individually or collectively by Member States, and some decisions will require involvement and input at the EU-level or from TSOs.

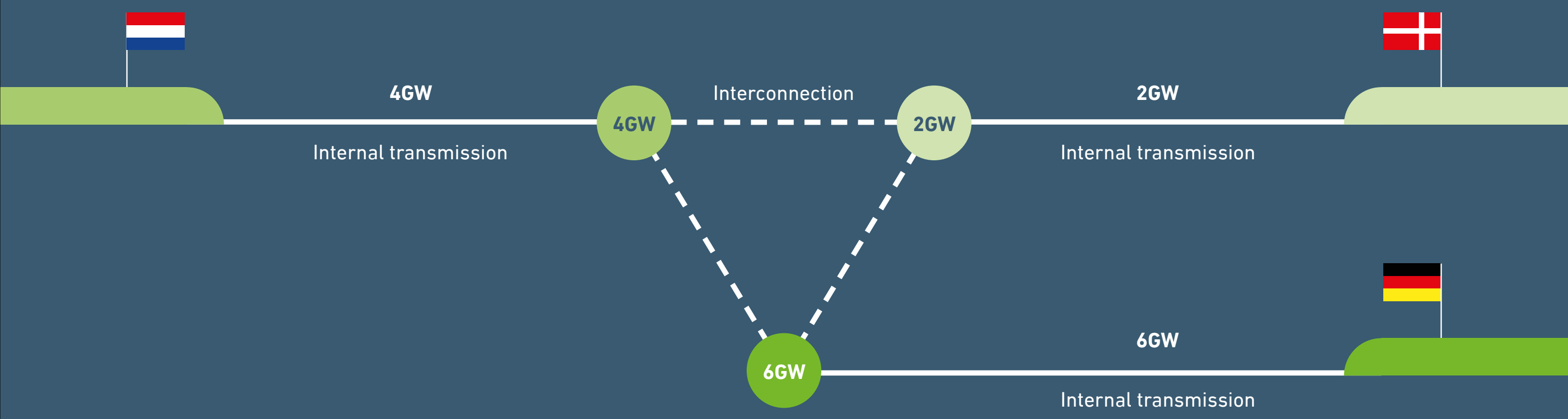
Key concept | Home market (HM) setup

Offshore wind farms bid and dispatch into their Home Market and receive the electricity price of the Home Market. The cable between the hub and Home Market is a hybrid asset, whereas the cables between the hub and the other bidding zones are cross-border interconnections.

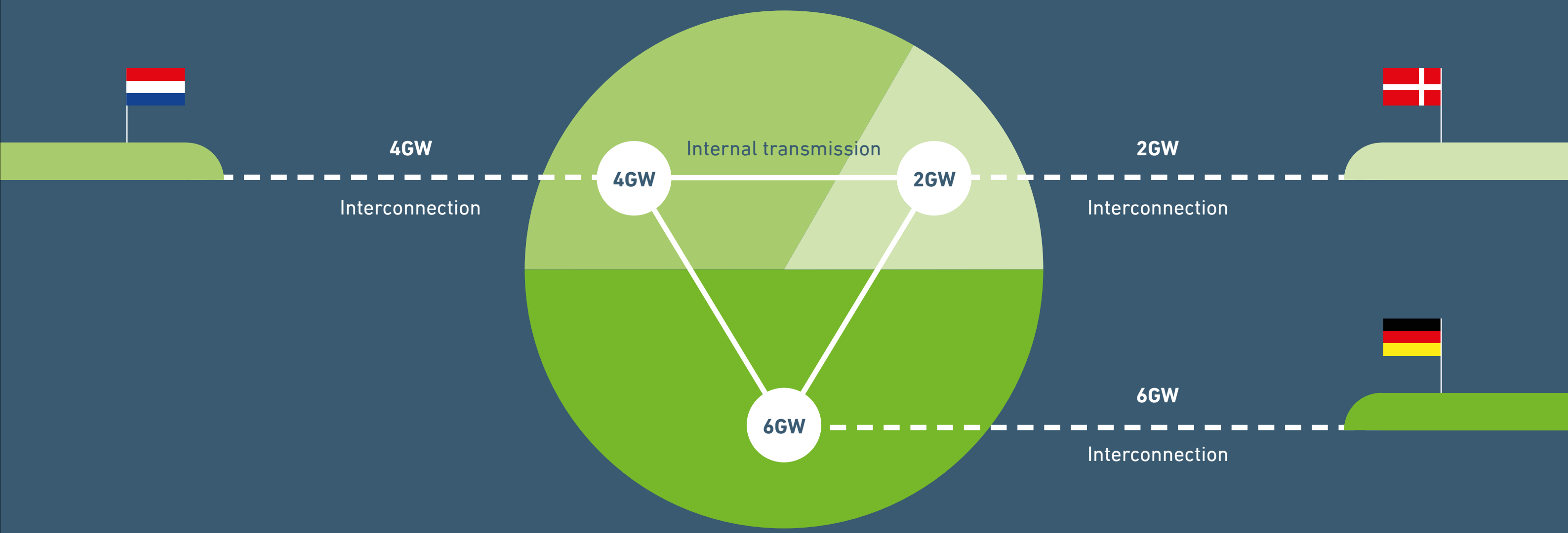
Market setups for hub-and-spoke projects

We consider two main offshore market setups for our analysis of hub-and-spoke projects; a home market setup and an offshore bidding zone market setup.

Home market (HM) setup



Offshore bidding zone (OBZ) market setup*



* There may be one or multiple offshore bidding zones, depending on transmission capacities.

Key concept I Offshore bidding zone (OBZ) market setup

The hub forms a separate offshore bidding zone, in which the offshore wind farms submit bids and are dispatched. Via market coupling, the offshore generation is matched with onshore demand. The electricity price within the offshore bidding zone depends on the flows on the interconnectors and the electricity prices of the connected bidding zones.

Four main themes can be identified in the topics and subtopics that show their interdependence:

- Cost Benefit Analysis & Cross-Border Cost Allocation (CBA/CBCA),
- Power-to-X,
- Market Setup and
- Governance models.

We illustrate the concept of interdependency through a deep-dive into the market setup topic.

Both home market and offshore bidding zone market setups have advantages and disadvantages in terms of regulatory compliance and implementation

The market setup is a key theme of interdependency between policy topics. Market setups[8] for hub-and-spoke projects define how offshore wind farms are allocated to specific bidding zones and subsequently how interconnection[9] capacity between these bidding zones is allocated. The market setup impacts the revenues of wind farm and interconnector operators.

Any market setup is required to be transparent, fair and non-discriminatory: key principles of the European Internal Energy Market. Compatibility with both European and national legal and regulatory frameworks is preferred as it eases market setup implementation.[xxx] Early decision-making and clarity on the market setup discussion is required for all involved stakeholders. This requires early participation of governments and national regulators to allow for timely decision-making by policymakers. We analysed the impact of two market design setups, the home market (HM) and offshore bidding zone (OBZ) market setups, to support two configurations of a hub-and-spoke project - distributed and centralised. Our analysis shows that:

- Both market setups are distinctive in their compliance with current European regulation (CACM[10] and CEP[11]). The OBZ setup can more readily comply with regulation around interconnection, compared to the HM setup that potentially requires regulation changes or exemptions.[12] In general, the OBZ setup results in more efficient flows as the setup follows the structural congestions in the network.
- The distributed hub configuration aligns with the authority boundaries between national territories (the Exclusive Economic Zones). The centralised hub system would require treaties between the connected countries or legislation and regulation changes to expand responsibilities of the respective stakeholders across country borders.[13]

Any change in market setup that involves an overhaul of fundamental European legislation requires significant time and effort and therefore poses a risk for the development timeline for a hub-and-spoke project. Case-specific derogations or exemptions should be avoided where possible to ensure a long-term and robust framework.

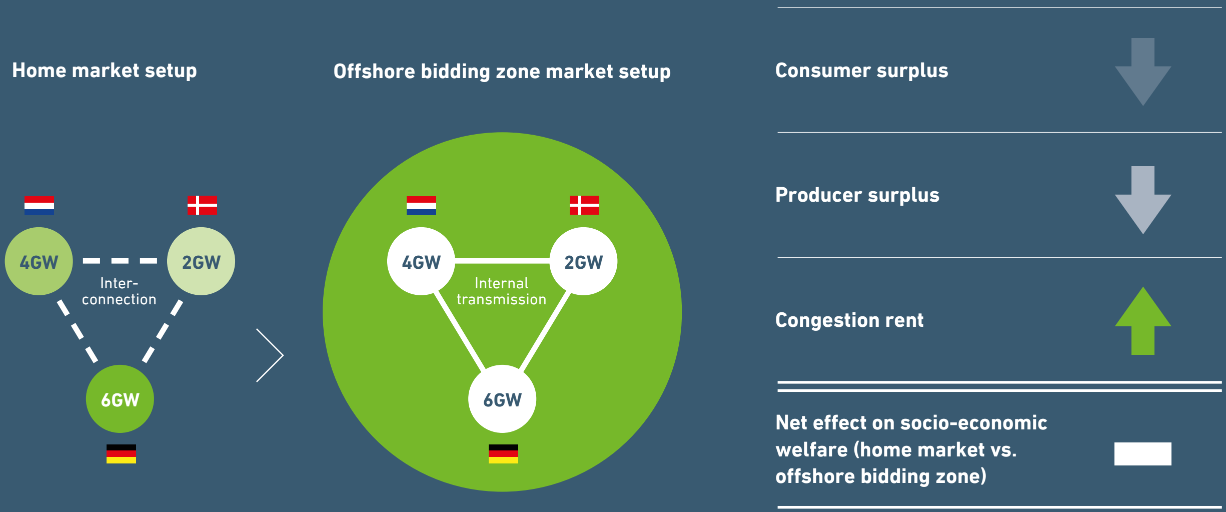
[8] Refer for a full explanation of the Home Market setup and the Offshore Bidding Zone setup to NSWPH, Market setup options to integrate hybrid projects into the European electricity market – Discussion Paper, April 2020.
[9] The terms interconnector and interconnection capacity refer to both infrastructure crossing member state borders and bidding zone borders.
[10] Article 33.1.c.i of the Capacity Allocation and Congestion Management Guideline, Commission Regulation (EU) 2015/1222, hereafter "CACM"
[11] European Clean Energy Package REGULATION (EU) 2019/943, hereafter "CEP", no priority access is provided to the offshore wind farms with respect to the infrastructure capacity.
[12] The 70% ruling states that TSOs should at least make 70% of the cross-border interconnection capacity available for cross-border trade. The 70% ruling might form a barrier in the HM setup when wind capacity of the hub is larger than 30% of the capacity of the transmission line to its home market. In the OBZ market setup, in contrast, the bidding zone borders are based on structural congestion and therefore the 70% ruling will not pose a barrier.
[13] This is only true if the respective stakeholders want to have their share in the roles and responsibilities corresponding to the development, ownership, operation and maintenance of a hybrid project.

Impact of market setup

Three-country distributed hub configuration

Impact on socio-economic welfare for the three-country distributed hub configuration when relatively comparing the offshore bidding zone market setup to the home market setup[14].

Stakeholders | Welfare impact across the markets[15]



Five-country distributed hub concept

Impact on socio-economic welfare for the five-country distributed hub configuration when relatively comparing the offshore bidding zone market setup to the home market setup[14].

Stakeholders | Welfare impact across the markets[15]

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[15] Note that upward arrows indicate a higher welfare under the OBZ market setup and downward arrows indicate a lower welfare under the OBZ market setup.

The relative effects of the selected market setup on socio-economic welfare are small in a three-country configuration, but potential benefits of an OBZ market setup are enhanced when more diverse markets are connected through the hub-and-spoke project

The choice of market setup impacts efficiency, price dynamics and income distribution between markets and stakeholders. We have conducted power market modelling to analyse this impact on two physical configurations of the hub-and-spoke project;[xxxi] a three-country configuration with the Netherlands, Denmark and Germany, and a configuration including additional connections to United Kingdom and Norway.

When relatively comparing both market setups for a three-country configuration, we found only a small difference in socio-economic welfare effects between market setup choice.[14] Potential benefits of an OBZ market setup are enhanced when more diverse markets are connected through the hub-and-spoke project. Additional connections to the UK and Norway add diversity. In the five-country configuration, an OBZ improves socio-economic welfare compared to the HM setup.

- For both the three and five-country configurations, the difference in market setup had little impact on consumer surplus, as wholesale electricity prices of the connected onshore bidding zones remain relatively unaffected regardless of market setup (less than 0.5% difference in prices for any of the core markets between the two market setups).
- We found a relative negative impact on overall producer surplus in the OBZ market setup compared to the HM setup, driven by a decrease in revenue for the hub-connected offshore wind farms under the OBZ market setup.
- Under the OBZ market setup we found higher congestion income compared to the HM setup. This is due to the fact that under the OBZ market setup all flows between the hub and respective countries are labelled as cross-zonal, whereas under the HM setup these are seen as internal flows within a home market for which no congestion income can be received.

[14] See for further details on the analysis and results: https://northseawindpowerhub.eu/wp-content/uploads/2021/02/NSWPH-Study_AFRY-Background-Report_Oct-2020_v500_FINAL.pdf

Next steps

As part of our work to support policy makers, we continually develop evidence-based discussion papers tackling new and emerging regulatory topics. For the upcoming feasibility phase of the project we have identified actions regarding the market setup, governance models and regulatory frameworks:

1 **Market setup**
We initiated additional analysis on a balancing framework for offshore bidding zones.

2 **Governance models**
The allocation of roles and responsibilities of infrastructure assets (e.g., electricity and hydrogen transmission, PtX, and interconnection) impacts principles for tender design and the scope of the first hub, as well as options for financing and cost-recovery of the infrastructure. We will further investigate potential governance models for hub-and-spoke projects through analysis culminating in the publication of a discussion paper.

3 **P2G Regulatory Framework**
We will investigate regulatory compatibility, such as regulation on hydrogen and PtX. We will publish a discussion paper describing the required structure of the market and regulatory framework for PtX to ensure efficient incorporation of offshore wind targets and wider system efficiency.

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Coming soon
NSWPH discussion paper on CBA frameworks
NSWPH discussion papers on Power-to-X

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